AMMRC CTR 75-22

MACHINE CASTING OF FERROUS ALLOYS

October 1975

M.C. Flemings, *et al*

Department of Materials Science and Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

INTERIM REPORT COVERING CONTRACT NUMBER DAAG46-73-C-0110

Prepared for
ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

MACHINE CASTING OF FERROUS ALLOYS

INTERIM TECHNICAL REPORT

ARPA CONTRACT NO. DAAG46-73-C-0110

June 1975

by

M. C. Flemings, R. Mehrabian, J. R. Melcher, R. G. Riek, K. P. Young
N. Matsumoto, D. G. Backman, F. S. Blackall, B.E. Bond, E. McHale, F. J. Schottman

Massachusetts Institute of Technology
Department of Materials Science and Engineering
Cambridge, Massachusetts 02139

Sponsored by: Defense Advanced Research Projects Agency, ARPA Order No. 2267

Program Code No. 4D10

Effective Date of Contract: January, 1973

Contract Expiration Date: December 31, 1976

Amount of Contract: $964,832.00

Contract Period Covered by Report: 1 July 1974 - 30 June 1975

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Army Materials and Mechanics Research Center under Contract No. DAAG46-73-C-0110.

TABLE OF CONTENTS

ABSTRACT

This is the third interim report describing research conducted at Massachusetts Institute of Technology as part of a joint university-industry research program on casting of ferrous alloys. It covers the period of the eighteenth to the thirthieth month of a four-year program. During this period the "Continuous Rheocaster" has been greatly improved and a machine casting system using semi-solid alloys "Thixocasting" has been developed and operated on pilot basis using a copper base alloy. Work has also continued on low temperature "model" systems, and on other supporting studies.

The high temperature "Continuous Rheocaster" described earlier has undergone extensive modification and development. It has been used to continuously produce a number of ferrous alloy slurries and a cobalt base superalloy slurry. The apparatus has now been optimized for continuous production of larger quantities of "Rheocast" ingots, and several hundred pounds have been produced of the "model" bronze alloy employed previously (905 alloy 88wt%Cu, 10wt%Cu, 10wt%Sn, 2wt%Zn). These ingots have been cut to size, reheated to the semi-solid range and cast using a newly developed "Thixocasting" system. This comprises an induction furnace to rapidly reheat the ingot sections to the semi-solid range, coupled to a commercial 125 ton cold chamber die cast machine. To date, more than 150 castings of a simulated D.O.D. part have been made in the bronze alloy.

Results of this work confirm that castings with good surface quality are obtained with internal soundness substantially improved over that of die castings made from superheated metal.

Internal die temperature measurements were made during the casting of both liquid and semi-solid bronze alloy 905. Computer calculations indicate that use of semi-solid charge, as opposed to superheated liquid charge, significantly reduces die surface temperature, (by a factor of 4), rate of surface heating, (by a factor of 7), and maximum surface temperature gradient, (by a factor of 8).

The low temperature "Continuous Rheocaster" has been used with the model Sn-Pb alloys employed previously to examine the effects on the slurry structure of cooling rate, shear rate, composition and volume fraction solid. Primary particle size decreased markedly with increasing cooling rate, in the range 0-800°C $min.^{-1}$ and to a lesser extent with increasing shear rate in the range 0-1000 $sec.^{-1}$. Particle size increased with fraction solid, particle sizes were in the range of 60-250μm. The successful production of pure Sn, Sn-Pb eutectic and near eutectic slurries has confirmed the feasibility of Rheocasting alloys of narrow freezing range.

The feasibility of a modified "Thixocasting" process termed "Clap Casting" has been demonstrated using as a model an aluminum-copper alloy. This process eliminates both crucible and alloy injection equipment while automating metal transfer. It is, therefore, particularly attractive for high temperature alloys.

Two different types of electromagnetic injectors have also been studied and comparisons between them made on the basis of experiment and theory. The first is an "induction" machine described earlier, the second is a "universal" machine. Theory and experiment agree well in both machines. A simply and inexpensively constructed apparatus can propel metal at velocities of 20 m/sec. corresponding to casting pressures of 400 psi.

INTRODUCTION AND GENERAL SUMMARY OF PROGRAM TO DATE

In January, 1973, a joint university-industry research activity was undertaken to develop an economical method of machine casting ferrous alloys. A central concept in the original planning was that the ultimate development of such a process would depend on introduction of radically new technology to the industry, rather than by introducing minor changes to existing processes or by using better materials in existing equipment.

A phased program of research was planned and is currently being carried out. The first phase was devoted to innovating and testing innovative concepts. Subsequent phases are being devoted primarily to selecting a few of these concepts, testing them on "model systems" (e.g., bronze and cast iron) and then scaling the process up to steel. A final phase is planned to measure economic as well as technical feasibility.

The portion of this program being conducted at Massachusetts Institute of Technology has been primarily on machine casting of semi-solid alloys, into re-usable metal dies. A variety of casting concepts have been explored as reported herein and in previous reports,[1,2] but major emphasis of the work has been on two processes: Rheocasting and Thixocasting. The machine casting systems developed for these casting processes are as follows:

Rheocasting

Producing a fluid semi-solid slurry and casting this directly. The system developed is shown schematically in Figure 1. Slurry is produced continuously or semi-continuously in a continuous "Rheocaster", and then a metered portion of this slurry is transferred directly to the shot chamber of a cold chamber die casting machine.

Thixocasting

Reheating slugs of metals that were previously Rheocast, and casting of these slugs. The system developed is shown schematically in Figure 2. Slurry is first produced using the continuous Rheocaster, and the metal so produced is completely solidified. Slugs of predetermined weight are then re-heated to a desired fraction solid, transferred to the shot chamber of a die casting machine, and die cast.

Both the Rheocasting and Thixocasting systems described above were developed and tested during the first twelve months of this program, using tin-lead as model system. Construction was also begun of a continuous Rheocaster that would be suitable for alloys of intermediate temperature range (bronze, cast iron). This work was described in the first report of this program,[1] covering work conducted during the year ending January, 1974.

These laboratory Rheocasting and Thixocasting systems were further developed during the next six months of the program, as summarized in a second report[2] covering the period January - July, 1974. An important result during that period was that the continuous Rheocaster was shown to work for both bronze and cast iron, and a limited number of castings were then Rheocast using a small laboratory ("home made") die casting machine.

Results of the next twelve months of the program (the period ending July, 1975) are summarized herein. A commercial die casting machine (125 ton, B. T. Greenlee machine) has been installed and work has focused on the Thixocasting process. The important applied aims of the program during this period have been to:

1. Install and demonstrate operability of a Thixocast system that would work on a pilot production basis.
2. Improve casting rate and reliability of the continuous Rheocaster.
3. Produce significant quantities of a "model" alloy of intermediate melting point (bronze) in the continuous Rheocaster and produce castings of this material in the above Thixocast system.
4. Modify the continuous Rheocaster and demonstrate its applicability to casting of stainless steel and superalloys.

Each of these aims have been met, and results are described in Chapters 1 and 2 of this report. Chapters 3 and 4 deal with more fundamental studies that are closely related to the major applied objectives of the program. Chapter 3 is on thermal studies of die behavior in Rheocasting and Thixocasting and Chapter 4 is on structure control in continuous Rheocasting.

Chapters 5 and 6 describe relatively small activities designed to study other process innovations that might be used in conjunction with Rheocasting and Thixocasting. Chapter 5 describes work on a process we have termed "clap casting" and Chapter 6 is on development of an electromagnetic discharge device to replace the plunger of a die casting machine.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report. ARPA Contract DAAG46-C-0110, 1 January - 30 December 1973, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.
2. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report. ARPA Contract DAAG46-C-0110, 1 January - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

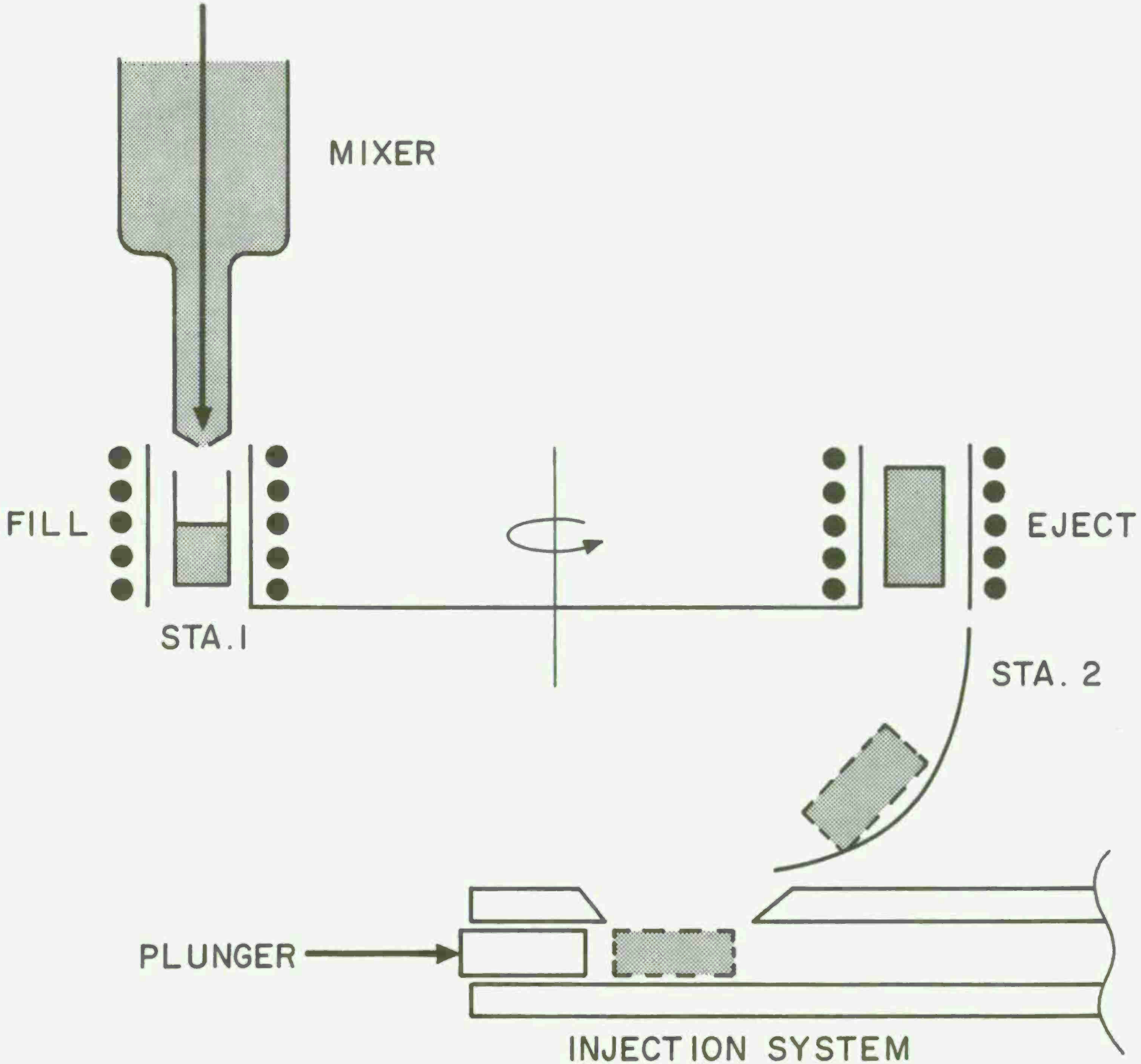


Figure 1. Schematic of a hot "Rheocast" system.

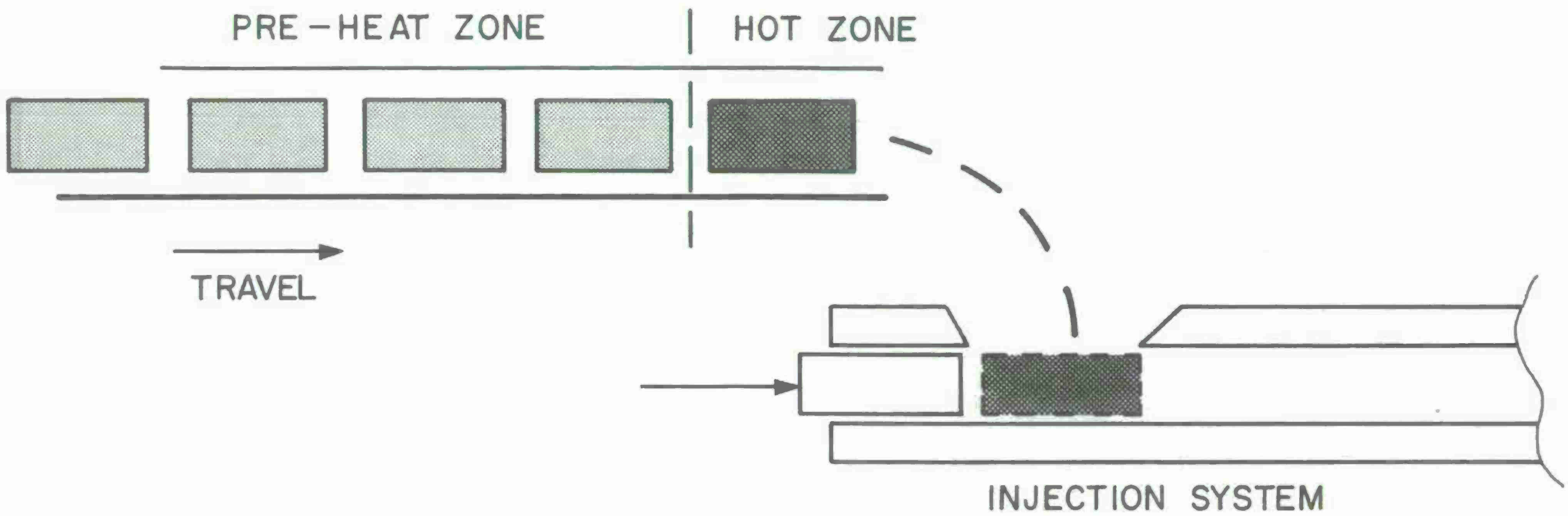


Figure 2. Schematic of a "Thixocast" system.

TECHNICAL AND ECONOMIC ADVANTAGES OF RHEOCASTING AND THIXOCASTING

It is appropriate at this point in the program to review our current understanding of technical advantages of Rheocasting and Thixocasting. The advantages, which it is believed will lead to a technically and economically desirable process, are:

- Less thermal shock to mold and shot chamber
- Less turbulence in mold filling
- Less metal shrinkage in the die cavity
- Altered metallurgical structure
- Reduced energy consumption
- Improved materials handling

The major factor limiting development of a ferrous die cast process heretofore has been intolerably short die and shot chamber life. A central concept of this program, and an underlying reason for its existence, has been that semi-solid metal will result in much less thermal shock to these components of the machine, and therefore to much longer shot chamber and die life. Experimental verification of this concept remains a major program objective. Two results, however, offer strong encouragement.

Firstly, direct thermal measurements just behind the mold face show much less die heating when Thixocast metal is cast than when fully liquid metal is cast. Computer extrapolation of these results to the die face

shows that for Thixocast metal (bronze in this case) versus fully liquid metal, maximum die surface heating is reduced by a factor of 4, surface heating rate is reduced by a factor of 7, and initial surface thermal gradient is reduced by a factor of 8. These results are reported in Chapter III of this report. It should be emphasized that these are preliminary results of a continuing study.

A second encouraging observation (as yet much less quantifiable) is that the Thixocast metal heats the shot chamber and plunger much less than does fully liquid metal. As expected, the Thixocast metal remains in a compact "glob" when placed in the shot chamber, with relatively little thermal contact between it and the chamber walls or plunger tip. Liquid metal, on the other hand, spreads the length of the shot chamber.

The fact that there is less turbulence in mold filling with Rheocast or Thixocast metal has been demonstrated with high speed movies.[(1)] This is certainly one factor leading to less thermal shock of the die cavity. It also leads to less porosity in the solidified casting from entrapped air. This fact, together with the lower amount of solidification shrinkage of semi-solid alloys, results in the now firmly proven observation that Rheocastings and Thixocastings are inherently sounder than die castings produced of fully liquid metal (see, for example, Chapter II of this report).

The metallurgical structure of Rheocastings and Thixocastings is markedly different from that of usual cast metals. Details of the structure and potential advantages of the structure modification achieved have yet to be fully explored. As one example, the grain size of a Rheocast or Thixocast casting is inherently extremely fine, much finer than the grain size of usual castings. The grain size can be controlled by controlling the size (and hence number) of the solid particles in the original Rheocast material. A major part of the work presented in Chapter IV deals with ways to control this original particle size (and, therefore, grain size). The work is on the model system tin-lead. Beyond this, we do not yet know a great deal about structural details or structure-property relations, and studies in this area are planned as an important part of future work.

Rheocasting and Thixocasting offer the potential for economies in energy consumption and materials handling costs. For example, in one potential embodiment of the Thixocasting system, the original Rheocast slugs would be made by a continuous casting process. This would require no significant additional energy input over conventional continuous casting. The slugs would then be shipped to the die casting foundry where they would then be only partially remelted by highly efficient rapid induction heating, resulting in substantial energy saving over conventional melting processes. The semi-solid slugs would then be automatically fed to the chamber of a die casting machine, eliminating the need for melting, hand ladling, and incidentally the necessary pollution control equipment that accompanies melting operations.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report. ARPA Contract DAAG46-C-1001, 1 January - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

PUBLICATIONS, PAPERS, AND PATENTS TO DATE

In addition to this report, two earlier reports describe work at M.I.T. during the first 12 months and subsequent 6 months of the program.[1,2] In addition, a large number of papers have been published, that describe various technical aspects of the program at M.I.T. These are listed as References 3 to 11.

Much of this work has been conducted by graduate students, and has formed the basis of their thesis research. To date 3 doctoral theses and 5 Master's theses have been completed as part of this program. These are listed as References 12 to 19.* Currently, as part of this program, there are 3 Doctoral theses and 2 Master's theses in progress.

A number of patents have been applied for as a result of technical developments of this program. Of these, one has been issued. It is on the continuous Rheocaster and is listed as Reference 20. Others are expected to issue in the near future.

---

* Work of Spencer and part of the work of Joly were conducted under the initial fundamental program sponsored by Army Research Office, Durham, North Carolina, that led to this applied activity. All other theses papers and reports listed come directly from this Advanced Research Projects Agency Sponsored Program.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January - 30 December 1973, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.
2. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January - 30 June 1974.
3. D. B. Spencer, R. Mehrabian, M. C. Flemings, "Rheological Behavior of Sn-15% Pb in the Crystallization Range", Met. Trans., v. 3, 1972, pp. 1925-1932.
4. R. Mehrabian, M. C. Flemings, "Die Casting of Partially Solidified Alloys", Trans. AFS, v. 80, 1972, pp. 173-182; Die Casting Engineer, July-August, 1973, pp. 49-59.
5. M. C. Flemings, R. Mehrabian, "Casting Semi-Solid Metals", Transactions, International Foundry Congress, Moscow, 1973, AFS Trans., v. 81, pp. 81-88.
6. E. F. Fascetta, R. G. Riek, R. Mehrabian, M. C. Flemings, "Die Casting Partially Solidified High Copper Content Alloys", Die Casting Engineer, September-October, 1973, pp. 44-45.
7. R. Mehrabian, M. C. Flemings, "Machine Casting of High Temperature Alloys", to be published in Proceedings of ASM Materials Science Seminar on New Trends in Materials Processing, held in Detroit, October, 1974.

8. R. G. Riek, K. P. Young, N. Matsumoto, R. Mehrabian, M. C. Flemings, "Rheocasting of Ferrous Alloys presented to the Society of Die Casting Engineers, Detroit, March,1975.

9. R. Mehrabian, M. C. Flemings, "Casting in the Liquid Solid Region", New Trends in Materials Processing, Society of Metals, Metals Park Ohio, to be published.

10. P. A. Joly, R. Mehrabian, "Rheology of Metals", to be published.

11. R. G. Riek, A. Vrachnos, K. P. Young, N. Matsumoto, R. Mehrabian, "Machine Casting of a Partially Solidified High Copper Content Alloy", presented to A.F.S., St. Louis, 1975.

12. D. B. Spencer, "Rheology of Liquid-Solid Mixtures of Lead-Tin", Sc.D. Thesis, 1971, M.I.T.

13. P. A. Joly, "Rheological Properties and Structures of a Semi-Solid Tin-Lead Alloy, Sc.D. Thesis, 1974, M.I.T.

14. D. G. Backman, "Machine Casting of High Temperature Alloys", Sc.D. Thesis, 1975, M.I.T.

15. E. F. Fascetta, "Rheocasting of Copper and Iron Base Alloys", S.M. Thesis, 1973, M.I.T.

16. A. Vrachnos, "Machine Casting of a Partially Solidified High Copper Content Alloy", S.M. Thesis, 1975, M.I.T.

17. F. Blackall, "The Delivery and Casting of Semi-Solid Metals", S.M. Thesis, 1975, M.I.T.

18. V. Laxmanan, "Rheocasting of Superalloys", S.M. Thesis, 1975, M.I.T.

19. B. Bond, "Machine Casting of Semi-Solid Bronze", S.M. Thesis, 1975, M.I.T.

20. M. C. Flemings, R. Mehrabian, R. G. Riek, United States Patent Number 3,902,544, September 2, 1975, "Continuous Process for Forming an Alloy Containing Non-dendritic Primary Solids."

CHAPTER I. HIGH TEMPERATURE CONTINUOUS RHEOCASTER

Summary

The high temperature "Continuous Rheocaster" (continuous slurry producer) has undergone extensive modification and development. A number of ferrous alloys and a cobalt-base superalloy have been processed with success. The apparatus has now been optimized for continuous production of large quantities of "Rheocast" ingots. These ingots will be used as charge material in a high pressure die casting machine (i.e., in "Thixocasting").

Introduction

At the beginning of this contract period, the Continuous Rheocaster had been operated successfully using bronze and cast iron alloys. These were model alloys which allowed various convenient flexibilities in operation and testing of the apparatus. During this contract period the emphasis was on two areas of developments. The first area was materials improvement in the equipment so as to increase its reliability and durability with the more severe demands of ferrous slurry production. The second area of development was that of design modification to increase the efficiency and rate of productivity of the equipment.

The Continuous Rheocasting Equipment

The equipment, as it exists presently for ferrous slurry production, is shown in Figure 1. Figure 2 is a schematic cross section of the furnace.

The interior of the crucible can be visualized as two connected chambers. The upper chamber (3 5/8 inches in diameter by 7 1/2 inches high) is a molten alloy reservoir. In the lower chamber (1 1/4 inches in diameter by 6 inches high) the alloy is vigorously agitated while heat is extracted from it. The agitation is accomplished by a rotating ceramic shaft which extends to the bottom of the lower chamber. The shaft seats against a hard ceramic insert which forms the exit nozzle for the slurry. The shaft can be raised and lowered while rotating to act as a valve controlling the flow rate of the exiting slurry.

The design and construction of early versions of the apparatus have been discussed in previous reports.[1,2] Substantial modifications and improvements have been made during this contract period. These are discussed below; many are embodied in Figure 2.

Equipment Modifications

The induction coil which surrounds the mixing chamber has been relocated from a position outside the furnace shell to a location within the shell in rammed refractory about 1/2 inch from the crucible wall, Figure 2. With this configuration, heat can be extracted from the mixing chamber via the coil cooling water. This more efficient cooling of the mixing chamber allows faster slurry production rates. With this modification the rate of heat extraction is such that the apparatus can produce ferrous alloy slurries at the rate of about 90 lbs./hr.

As Figure 2 indicates, a separate induction coil has been added to the apparatus below the mixing tube coil. This coil heats the crucible in the area of the exit nozzle and the cylinder below the nozzle. It allows the exit nozzle temperature to be controlled independently from the temperature in the mixing tube. This added control reduces the chance of alloy blockage in the nozzle, especially during intermittent flow operation.

Hollow ceramic thermocouple protection tubes have served successfully as rotors for ferrous alloys. The tubes are 18 1/2 inches long by 1 inch O.D., with 1/8 inch wall thickness. The lower end of the tube is hemispherically closed. Tubes of a mullite and glass composition (stoichiometric mullite plus 15% free silica) have performed successfully in producing hypoeutectic cast iron slurries. Tubes of high purity Al_2O_3 have been used with success for the superalloy and ferrous alloys tried thus far. Table I summarizes rotor performance to date.

Tests have indicated (in bronze ingot production using a graphite rotor) that at high cooling rates in the mixing chamber, a rotor of "square" cross section gives more efficient agitation of the slurry than a rotor of circular cross section at a given rotation rate. It has been observed that slurry flows more freely and controllably under a given set of conditions when a "square" cross section rotor is used. For example, at maximum cooling rate copper alloy 905 slurry flows freely from the mixing tube at a calculated maximum shear rate of 794 $sec.^{-1}$ using a "square" rotor. However, blockage in the mixing tube occurs at all

shear rates below 1190 sec.$^{-1}$ when using a round cross section rotor under the same conditions. Figure 3 shows the graphite rotor design now used for bronze slurry production. Rotors of similar design, slip cast in high purity alumina, are being purchased for use in ferrous slurry production.

Three thermocouples (Pt-Pt+10%Rh) have been placed along the inside wall of the mixing rotor, Figure 2. These thermocouples give a more accurate indication of the thermal profile within the mixing tube than the thermocouples at the crucible's outer wall. A set of rotary contacts has been designed which permits continuous monotoring of the EMF from these rotating thermocouples. The contacts are shown at the top of Figure 4a. The thermocouple leads pass through the center of the stainless shaft and are attached to a series of copper slip rings at the top end of the shaft. Electrical contact is made with these rotating rings by a set of spring-loaded carbon brushes. The system has been tested successfully under operating conditions during the production of stainless steel slurries (i.e., recording temperatures of 1450° to 1400°C at a rotation speed of 800 RPM).

A roller feed type charging device has been added to the equipment, as can be seen in Figure 4a. It allows continuous charging of rod stock up to 9/16 inches in diameter into the upper chamber. With the induction power to the upper chamber at its maximum of 30 KW, the feeding rate for steel is about 40 lbs./hr.

Operation

The equipment is usually operated to produce slurry continuously at the maximum possible rate. The following procedure is employed.

With about 10 pounds of initial charge in the upper chamber and the rotor in its seated position, power is supplied to the three induction coils. The chambers are heated at approximately the same rate to avoid thermal shock to the rotor. After the initial charge has melted, the top chamber is filled via the rod feeding device. The power to the top coil is then set to hold the metal at about 50°C superheat. The power to the bottom coil is set so as to hold the exit nozzle area at the desired temperature. At this point, with liquid metal in the mixing chamber, rotation of the stirrer is begun, and power to the middle coil is turned off. The middle induction coil now acts solely as a cooling coil for the slurry. When the thermocouples indicate that the desired temperature in the mixing chamber has been reached, the rotor is raised to allow flow through the nozzle. Regulation solely of flow rate at this point will control slurry temperature and fraction solid. Increasing the flow rate will reduce the metal residence time in the mixing chamber, thereby decreasing the fraction solid. Decreasing the flow rate will have the opposite effect. By regulating flow rate to stabilize the thermocouple read out, steady state slurry production can be achieved. Once slurry flow starts, the top chamber is replenished with alloy via the feeding device.

Ingot Making Procedure

The major use to which the Continuous Rheocaster will be put in the immediate future will be the production of ingots for subsequent Thixocasting, as described in Chapter 2.

The ingot molds consist of a stainless steel tube 1 3/8 inches in diameter by 6 inches long, with a lining of "Fiberfrax" paper approximately 1/16 inch thick. The insulating lining allows the slurry to cool slowly enough so that it fills the mold shape. It also prevents the ingot from adhering to the stainless tube. The lining is replaced each time the mold is filled. Six molds are held in a "Transite" container and separated by "Fiberfrax" packing, as illustrated in Figure 4b. In operation, slurry which is being continuously produced as described above is teemed into the room temperature ingot molds. Vibration of the platform on which the mold container is placed aids slurry fillout of the mold cavity.

Structure of the Semi-Solid Slurries

During the past twelve months, a number of high melting temperature alloy slurries have been made successfully in the continuous apparatus.

In addition to the copper and cast iron alloys reported previously,(2) several stainless steel compositions, a tool steel and a cobalt superalloy have been investigated. Table II lists these alloys, along with their nominal compositions and solidification ranges. Figures 5 and 6 illustrate

typical quenched microstructures obtained for several of the alloys investigated. As can be seen from the figures, the primary solid particles range roughly from 100 to 200 microns in mean diameter. The slurries in these figures range in fraction solid from about 0.3 to about 0.55. For comparison, several slowly cooled structures, typical of slurry ingot structures, are shown in Figure 7. The uniform equiaxed grain structure is present throughout all areas of the ingot.

Castings

In order to check the feasibility of casting stainless alloy slurries, several castings were made from semi-solid 440A stainless steel in the laboratory machine casting system described previously.[2] Figure 8 shows one of the castings produced with its biscuit still attached, along with the casting microstructure. Figure 9 gives an indication of the homogeniety of solid particle distribution in various regions of the casting. A somewhat more detailed account of this area of work has been published.[3]

Ingot Production

Thus far about 300 lbs. of continuously Rheocast ingots have been made in copper alloy 905, including one continuous run of 130 lbs. Figure 10 compares the quenched microstructure of continuously Rheocast copper alloy 905 with the corresponding ingot structure, which cools more slowly. The etchant used on the ingot sample reveals the segregation

which occurs during solidification, thereby indicating the location of what were solid particles when the ingot was cast. A small number of 440C stainless steel ingots also have been made in several test runs. Figure 11 compares the Rheocast quenched microstructure with the Rheocast ingot microstructure for this alloy. In the ingot structure the particles which were solid when the ingot was cast are effectively "masked" by the subsequent slow freezing in the mold. Larger scale ferrous runs are contemplated after receipt of the special square cross section rotors discussed previously.

With the present design, the maximum continuous slurry production rate (assuming a slurry of 0.5 fraction solid) for bronze is about 60 lbs./hr. The limiting factor is the heat extraction rate from the mixing tube. The continuous slurry production rate for ferrous alloys is 90 lbs./hr., as has been mentioned. However, in continuous operation, this production rate for ferrous alloys will be limited by the maximum melting rate of the current power supply, which is about 40 lbs./hr.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January - 30 December 1973, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts
2. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January 1974 - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

3. R. G. Riek et al., "Rheocasting of Ferrous Alloys", presented to S.D.C.E., Detroit, Michigan, 1975.

TABLE I

ROTOR MATERIALS TESTED IN HIGH TEMPERATURE ALLOYS

	MATERIAL	ALLOYS	RESULTS
1.	MULLITE - 15% SiO_2	CAST IRON	EXCELLENT; NEGLIGIBLE CHEMICAL AND MECHANICAL EROSION AFTER SEVERAL RUNS.
		440A STAINLESS STEEL	ROTOR SOFTENED AND PLASTICALLY DEFORMED IN SLURRY MIXING AREA.
2.	STOICHIOMETRIC MULLITE	440A STAINLESS STEEL	ROTOR SOFTENED AND PLASTICALLY DEFORMED IN SLURRY MIXING AREA.
3.	HIGH PURITY ALUMINA	440A STAINLESS STEEL 440C STAINLESS STEEL 304 STAINLESS STEEL M-2 TOOL STEEL HS 31 COBALT SUPERALLOY	EXCELLENT RESULTS WITH ALL ALLOYS TESTED; NEGLIGIBLE CHEMICAL AND MECHANICAL EROSION AFTER SEVERAL RUNS.

TABLE II

CONTINUOUSLY RHEOCAST HIGH TEMPERATURE ALLOYS

ALLOY	COMPOSITION	FREEZING RANGE(°C)
1. COPPER BASE ALLOY 905	Cu - 10%Sn - 2%Zn	1000 - 855
2. HYPOEUTECTIC CAST IRON	Fe - 2.6%C - 3.2%Si	1260 - 1130
3. 440A STAINLESS STEEL	Fe - 17%Cr - 1%Si 1%Mn - 1.1%C	1510 - 1370
4. 440C STAINLESS STEEL	Fe - 17%Cr - 1%Si 1%Mn - 0.6%C	1480 - 1370
5. 304 STAINLESS STEEL	Fe - 18.5%Cr - 9.5%Ni 0.08%C	1455 - 1400
6. M-2 TOOL STEEL	Fe - 6.25%W - 5%Mo 4%Cr - 2%V - 0.85%C	1435 - 1240
7. HS 31 COBALT SUPERALLOY	Co - 25.5%Cr - 11%Ni 7.5%W - 0.5%C	1395 - 1340

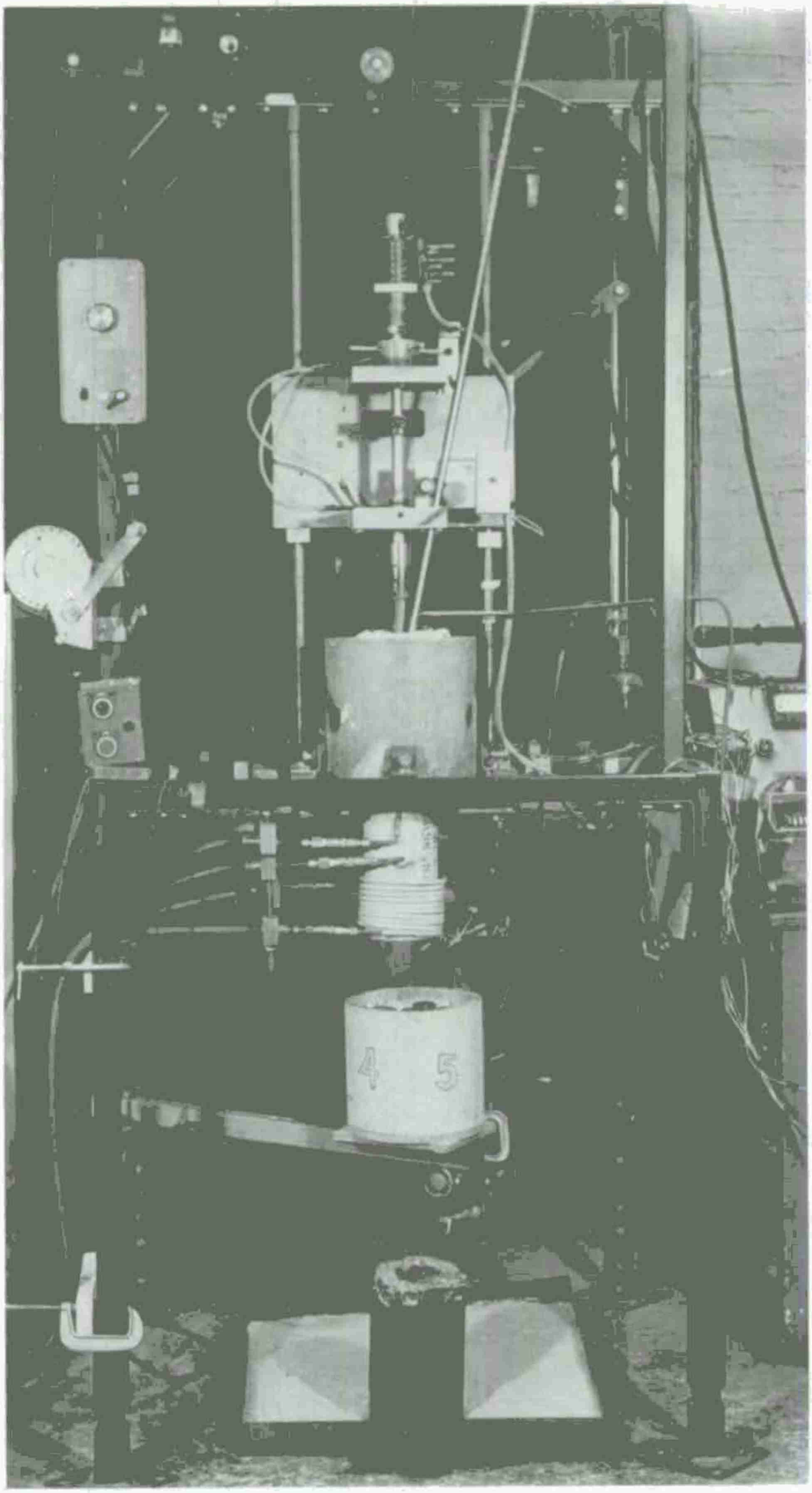


Figure 1. Overall view of the Continuous Rheocaster, set here for continuous ingot profuction

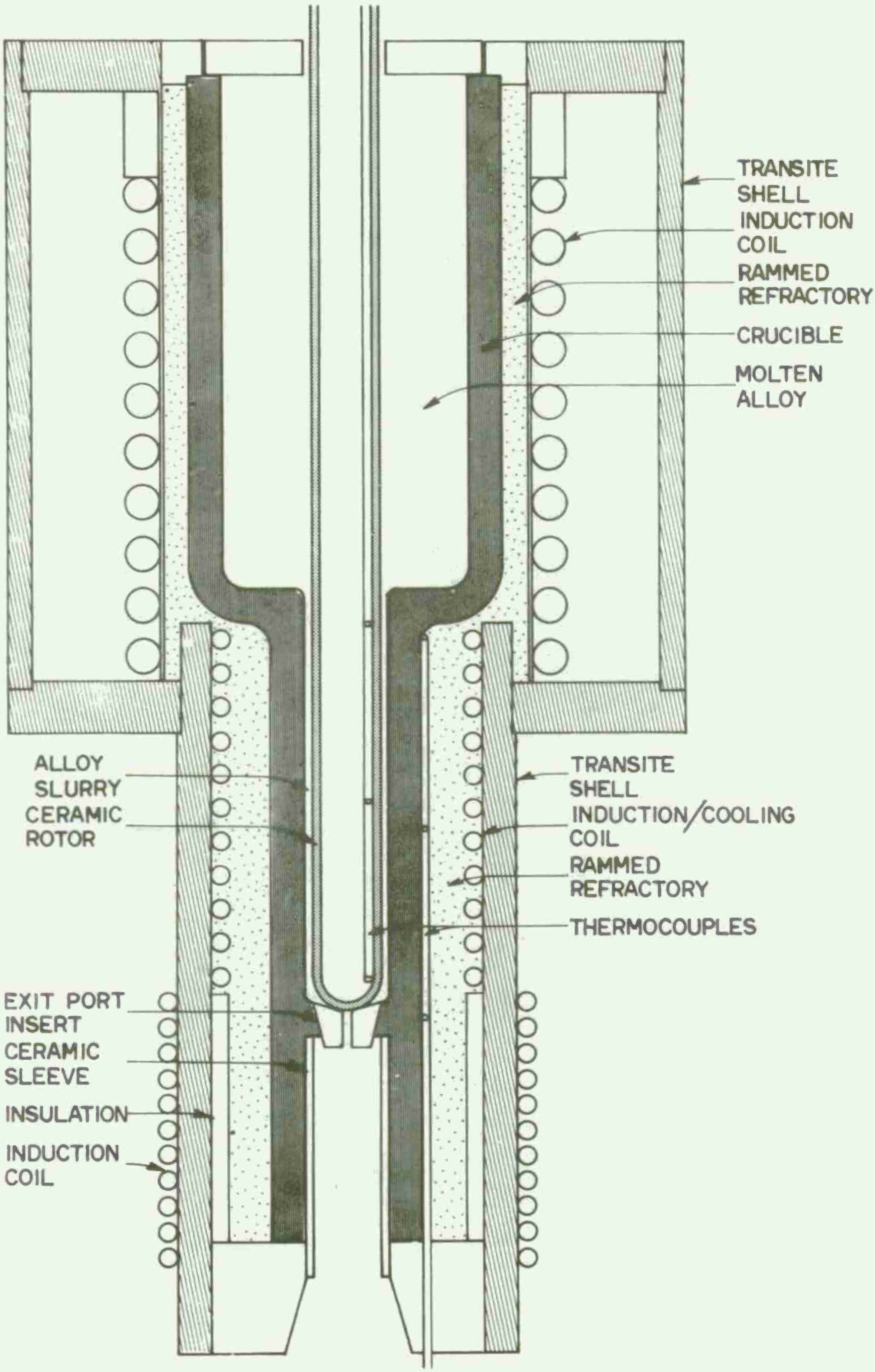


Figure 2. Schematic cross section of the furnace section of the Continuous Rheocaster.

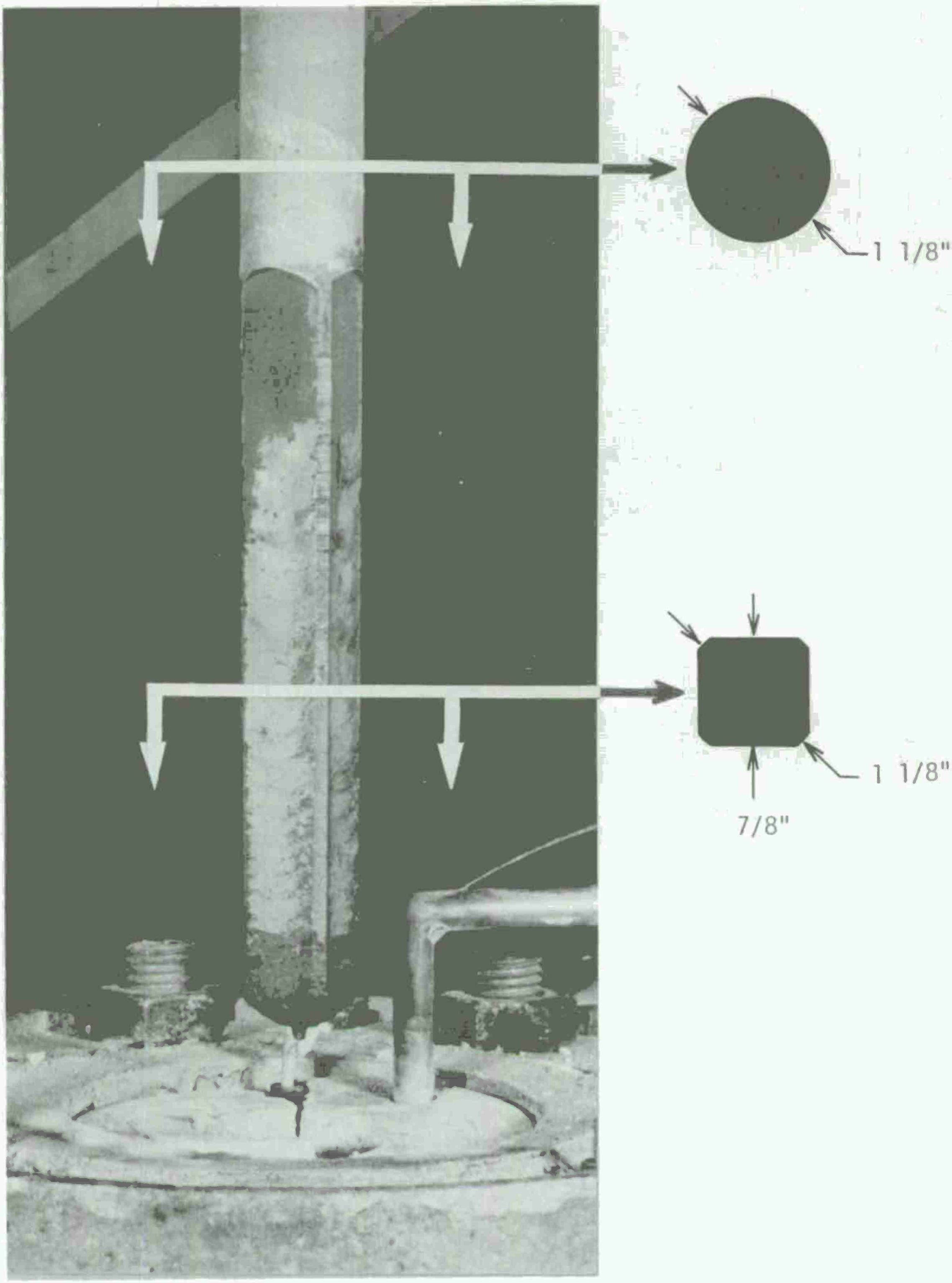


Figure 3. Graphite rotor presently used for 905 bronze ingot production. Square cross-section extends 6 1/2" from lower end of rotor.

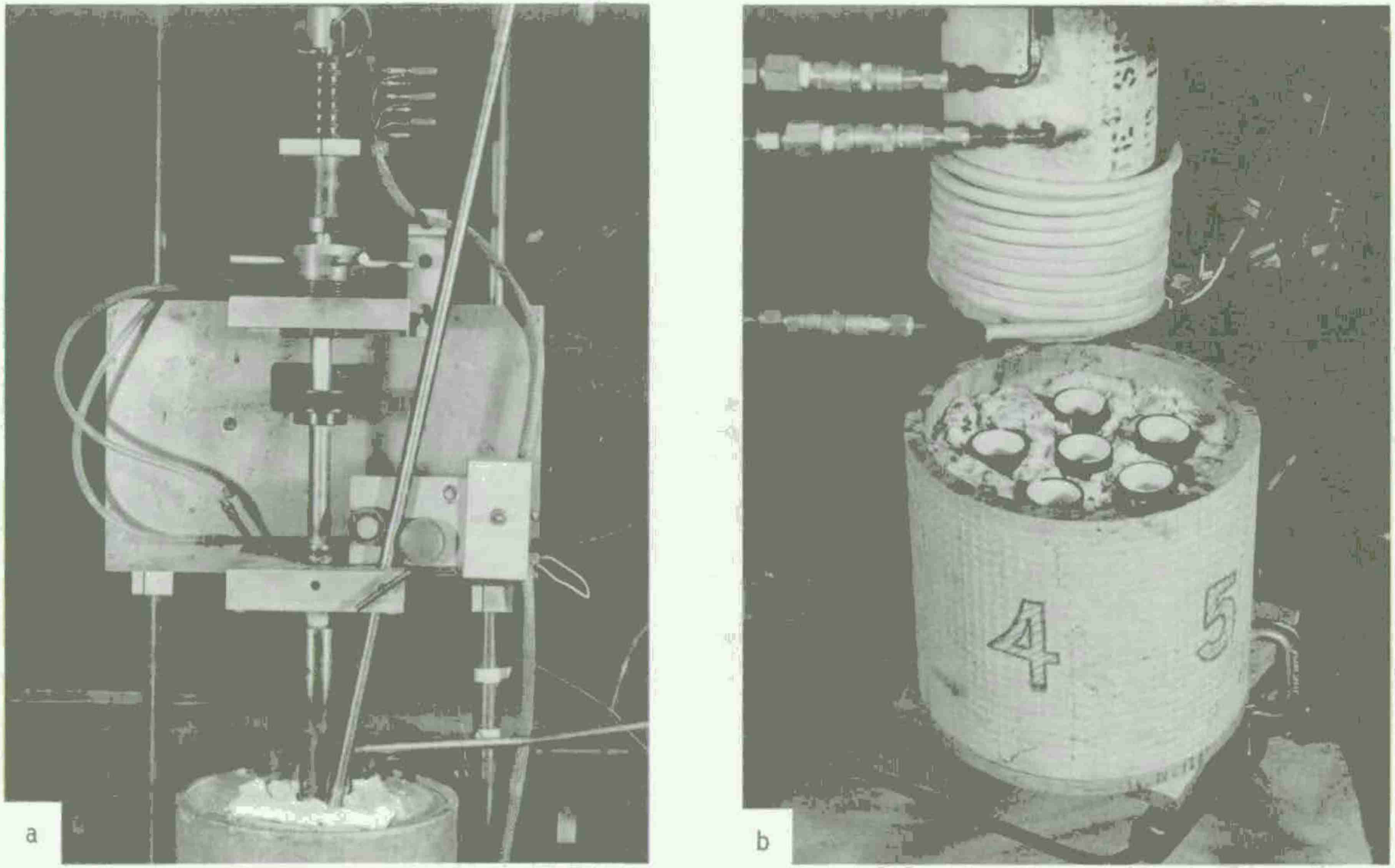


Figure 4. 4a: rotor drive mounting board showing attached roller feed device and rotary contacts for thermocouples. 4b: ingot container in position below the slurry producer.

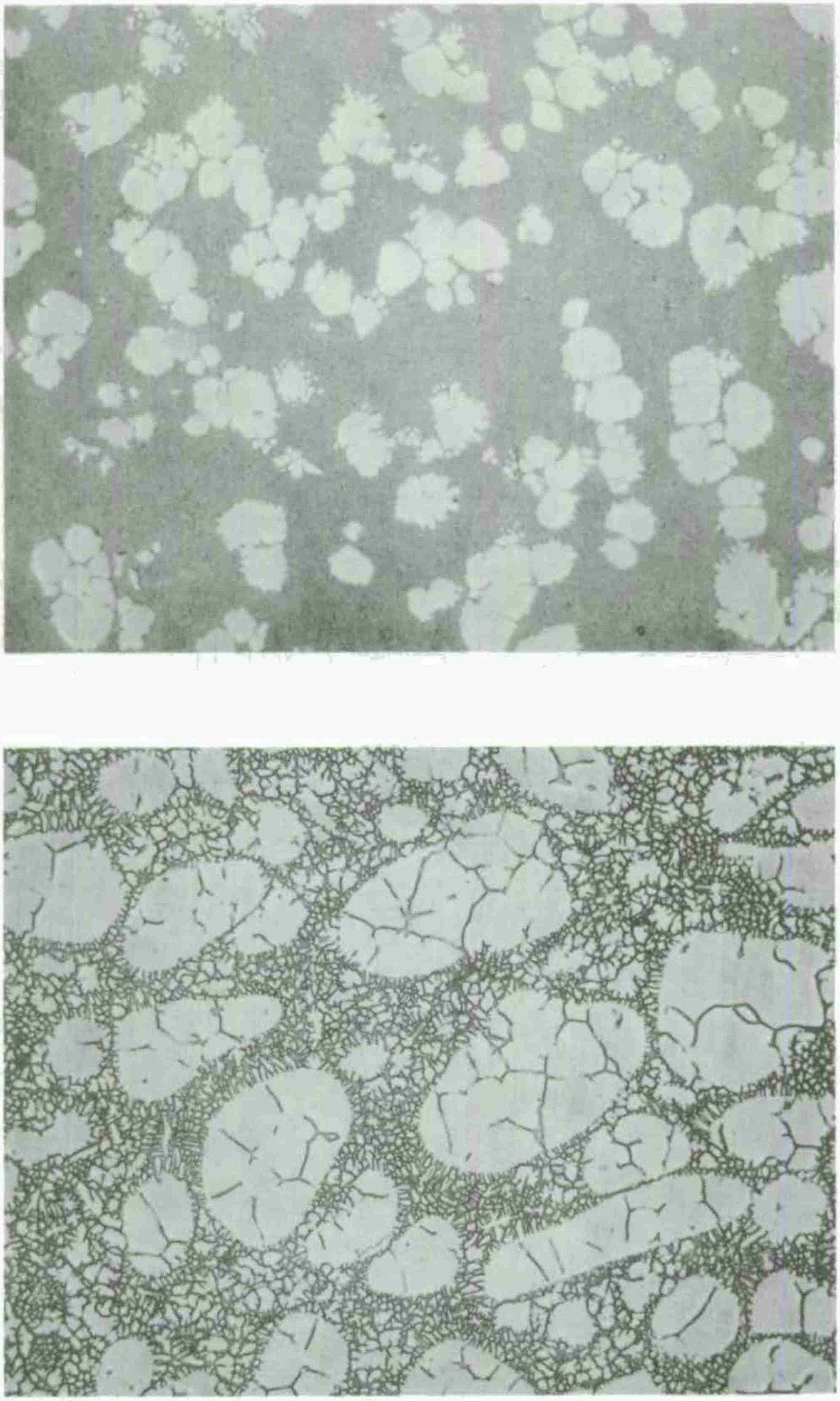


Figure 5. Microstructures of continuously produced semi-solid alloys. Samples were directly water-quenched. Top: 440A stainless steel. Bottom: HS 31 superalloy, 50X.

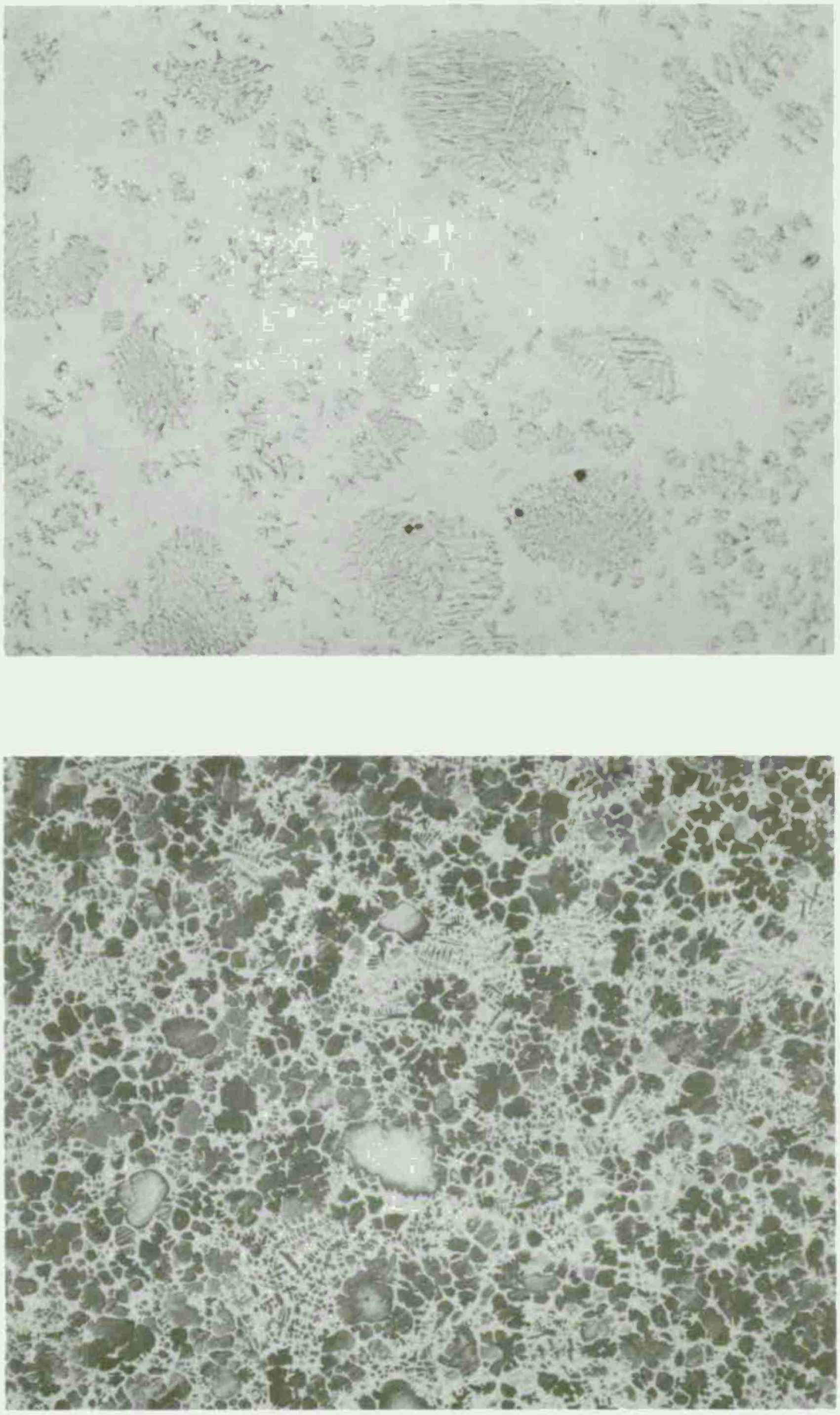


Figure 6. Microstructures of continuously produced semi-solid alloys. Samples were directly water-quenched. Top: 304 stainless steel. Bottom: 440C stainless steel, 50X.

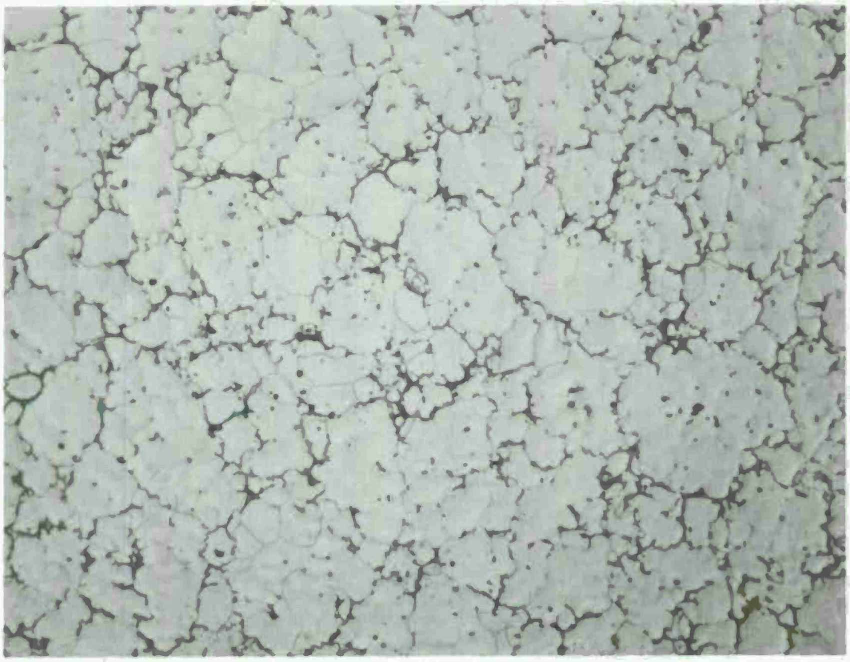


Figure 7. Microstructures of continuously produced semi-solid alloys. Samples were slowly cooled. Top: microstructure of HS 31 superalloy. Bottom: microstructure of M-2 tool steel, 50X.

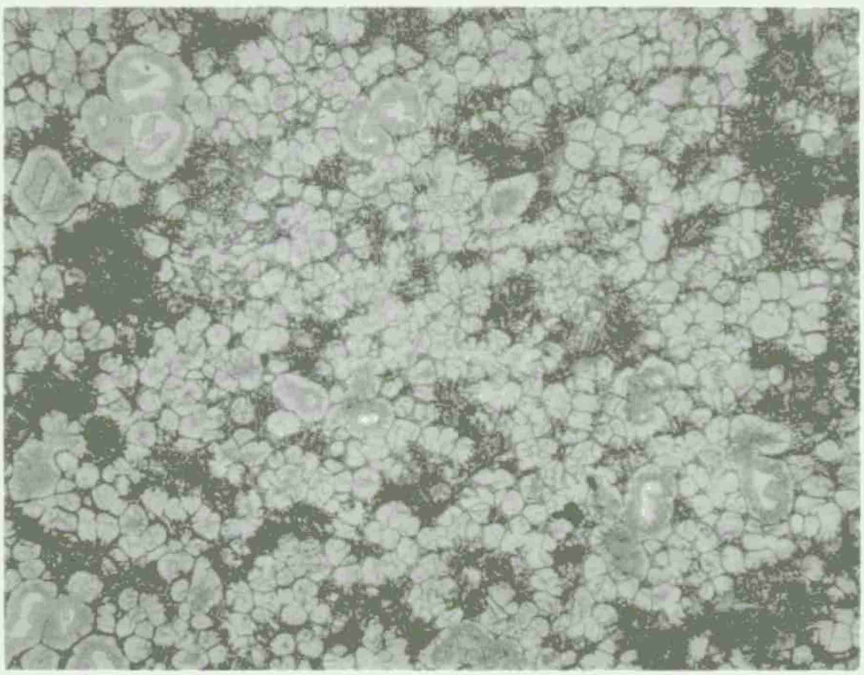


Figure 8. Top: 440A stainless steel casting produced from slurry charge in the low pressure laboratory machine casting system, 1X. Bottom: microstructure of the casting, 50X.

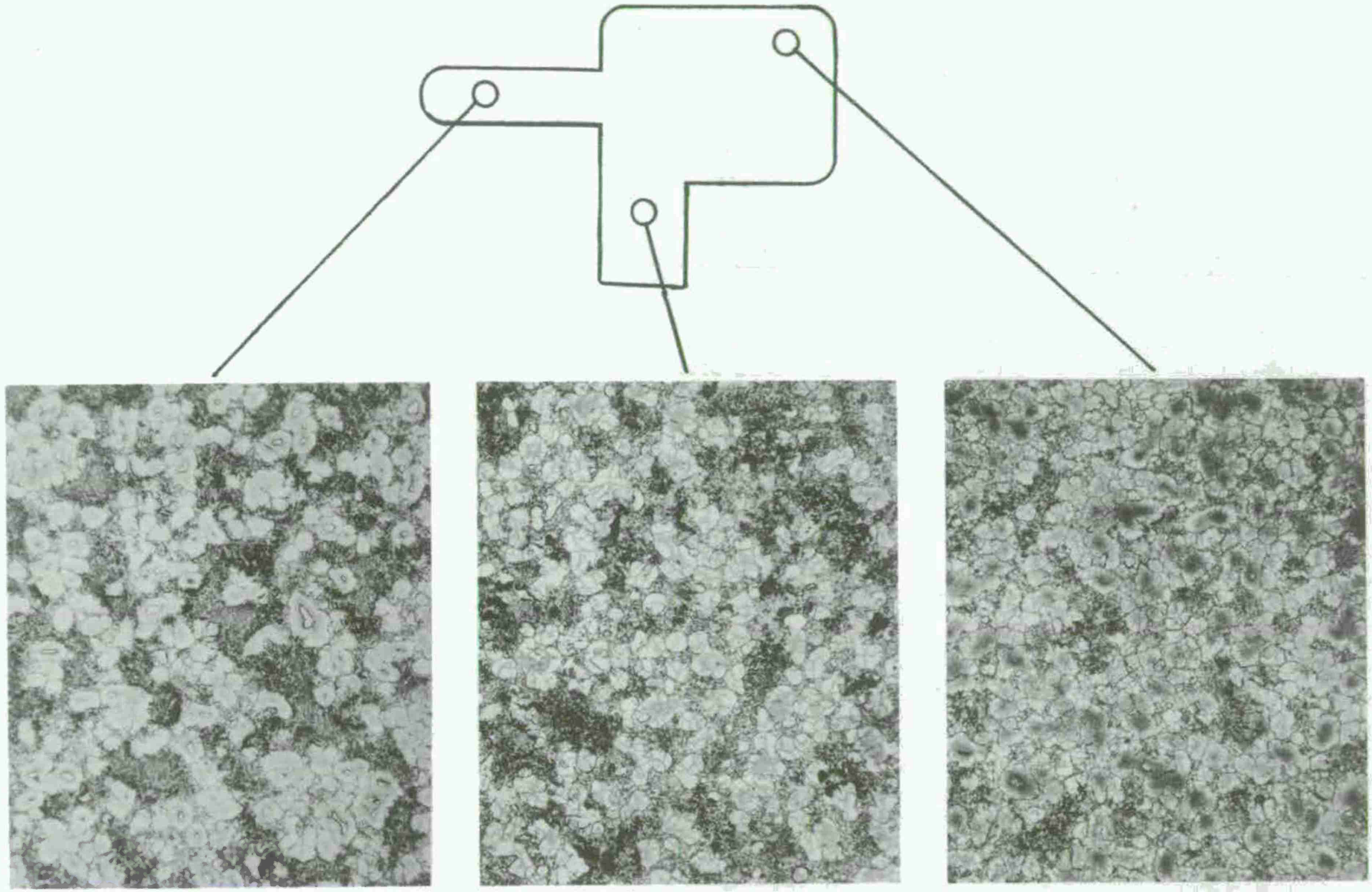
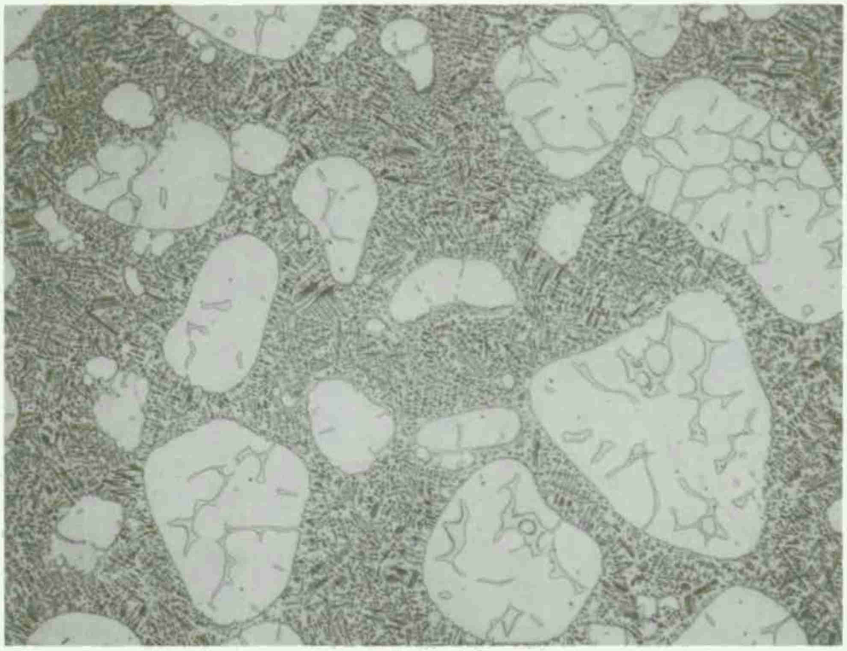


Figure 9. Photomicrograph showing homogeneous distribution of primary solid particles in various regions of a 440A stainless steel casting produced in the low pressure machine casting system, 50X.



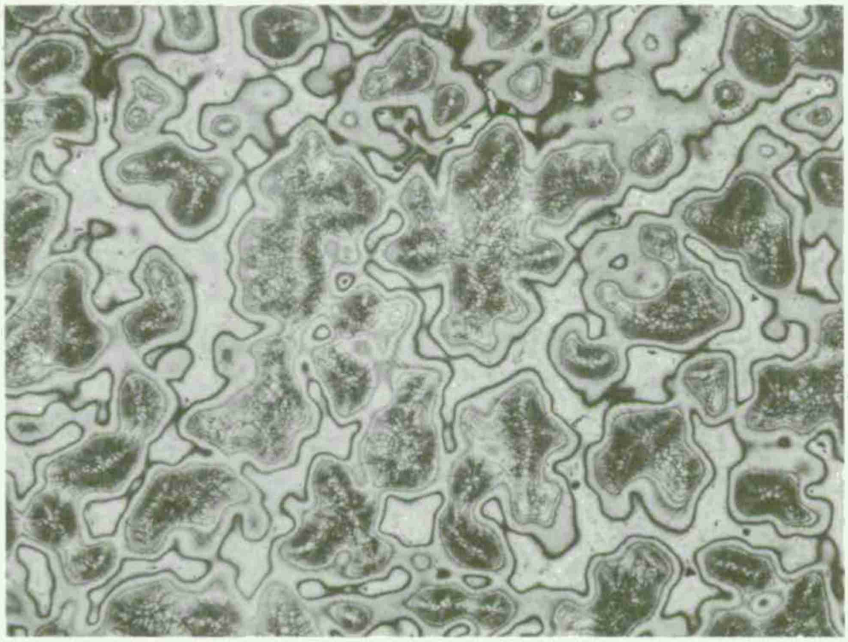


Figure 10. Microstructures of continuously produced semi-solid copper alloy 905 slurries. Top: rapidly cooled, water quenched sample. Sodium hydroxide plus hydrogen peroxide etch. Bottom: slowly cooled ingot. Chromic acid electrolytic etch, 100X.

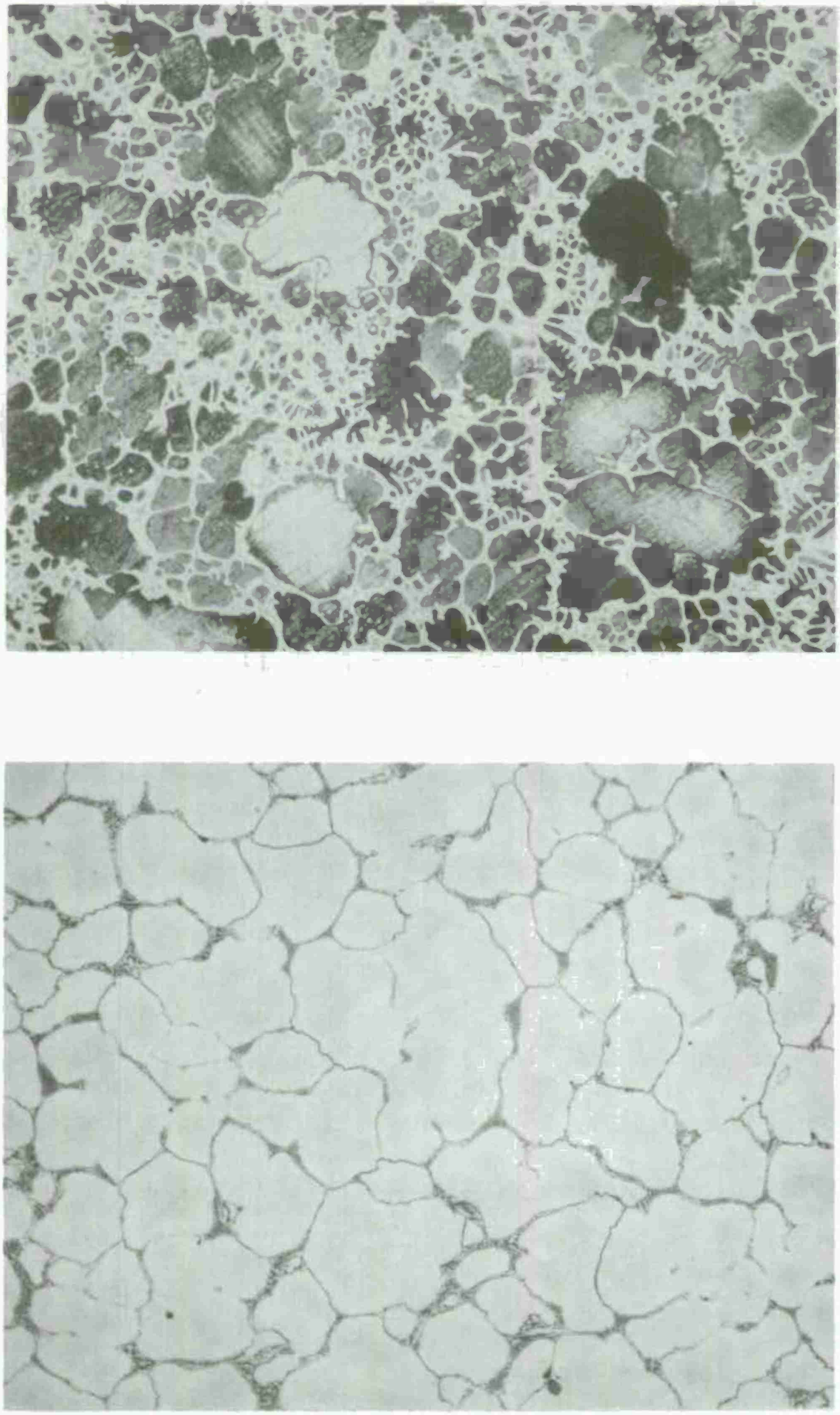


Figure 11. Microstructures of continuously produced semi-solid 440C stainless steel alloy slurries. Top: rapidly cooled, water quenched sample. Bottom: slowly cooled ingot, 100X.

CHAPTER II. MACHINE CASTING OF HIGH TEMPERATURE ALLOYS--DEVELOPMENT OF A THIXOCASTING SYSTEM

Summary

Following successful operation of a laboratory scale machine casting system for semi-solid slurries of high temperature alloys, a commercial horizontal cold chamber die casting machine and a reheating furnace have been coupled to produce a pilot plant scale "Thixocasting" system. This system has been developed using a model copper base alloy and over 150 castings of a simulated D.O.D. part have been produced to date. Results of this work confirm previous work that castings with good surface quality are obtained, with internal soundness substantially improved over that of die castings made of fully liquid metal. This soundness increases with increasing fraction solid of the Thixocast material. Results of this work will be applied over the coming months to casting of ferrous alloys.

Introduction

Previous work[1-3] using a laboratory scale low pressure system has confirmed the feasibility and demonstrated some of the advantages of machine casting semi-solid slurries of high temperature alloys. In this contract period, the development of the process towards pilot plant scale has continued. A commercial 125 ton locking force, horizontal cold chamber die casting machine has been purchased and installed. The machine has been

coupled to a furnace designed to reheat sections of ingots previously cast from semi-solid slurry. This "Thixocasting" system has been successfully operated to produce more than 150 castings of a simulated D.O.D. part in the model alloy employed previously: bronze 905 alloy (88wt%Cu, 10wt%Sn, 2wt%Zn, liquidus nominally 999°C).

Equipment

The Thixocasting system developed in this contract period comprises a commercial horizontal cold chamber die casting machine and a reheating furnace. A section view of the reheat furnace is shown in Figure 1, and a photograph in Figure 2. It consists of a 21 turn induction coil of 1/4 inch copper tubing wound around a 3 inch I.D., 1/8 inch thick mullite protection tube and insulated by a 7 inch I.D. 1/2 inch thick transite cylinder. Ends are covered with 1/2 inch transite plates in which 2 2/3 inch diameter holes are cut to seat the mullite tube. Rheocast slugs 2.15 inches long x 1.25 inches in diameter contained in silica sand crucibles can be raised into and lowered from the furnace by a mechanically linked foot pedal. While the base of the silica sand crucible itself serves as a thermal insulator, the top of the furnace is closed by firebrick through which inert (argon) atmosphere can be added. Power to the coil is supplied from a 50 KW, 3.8 KC Inductotherm unit and is regulated according to the output of a stainless steel sheathed chromel/alumel thermocouple placed in 1 inch deep, 5/32 inch diameter holes drilled in the center of each slug. More recently experiments have been undertaken to replace the disposable Co_2 bonded crucibles with re-usable thin wall clay-graphite crucibles.

The die casting machine, Figure 2, is a standard B.T. Greenlee high pressure die caster. It has a standard 1 3/8 inch diameter, water cooled plunger hydraulically powered by a 4 inch diameter piston, giving a pressure multiplication of 8.46 to 1. With accumulator pressure set at 800 psi, injection pressure is 6800 psi at the plunger tip. This plunger pressure can be increased to a maximum of 17000 psi (2000 psi on the piston) at any point in the stroke of the plunger by adjustment of the position of a simple trip switch. Plunger speed can be varied between 64 and 114 ft./min. as measured via high speed photography. Electrical resistance heating is supplied to both the shot chamber and the dies, the shot chamber being held at approximately 150°C. Two rod resistance heaters, nominally rated at 1500 watts, 240 volts, are contained in each die cavity plate and are controlled according to the temperatures measured by chromel/alumel thermocouples located centrally within each plate, close to the cavity.

The die steel used for the cavity, shot chamber and plunger tip was H-13 (composition: 0.40 C, 0.30 Mn, 1.00 Si, 5.00 Cr, 1.35 Mo and 1.00 V, weight percent). The die cavity was machined to produce a simplified version of the hammer of an M-16 rifle. The gate geometry was modified several times during the piloting stage to improve mold filling and surface quality. The gating finally evolved is shown in Figure 3. The gate is semi-circular, half-round in cross section, extending from the biscuit to the base of the hammer. At the gate/cavity junction the gate dimensions are a maximum width of 5/16 inch and a depth of 1/8 inch.

Procedure

After cooling, the ingots produced with the Continuous Rheocaster (Chapter 1) were cleaned of all "Fiberfrax" insulation and cut into slugs 2.15 inches in length. Holes were drilled along their axes (5/32 inches in diameter by 1 inch deep) for thermocouples and they were placed in sand crucibles. The crucibles were then raised into the reheat furnace and the thermocouple inserted, Figures 1 and 2. Maximum power was then applied to the furnace until the slug temperature approached the desired final reheat temperature (within 100°C) at which point the furnace power was regulated to 10 KW. This power was then further adjusted until the approximate desired final temperature was reached as determined from a previously derived fraction solid versus temperature plot.[1]

After reheating to the desired temperature (semi-solid or superheated liquid) the slugs were manually emptied into the shot chamber of the die casting machine and cast. Apart from an initial batch of 48 castings used for system development and the first one or two castings in each subsequent batch, injection pressure was maintained at 15200 psi. Plunger velocity, as best as could be controlled with the standard machine equipment was maintained at 64 ft./min. while die temperatures were varied in the range 70-360°C. Die lubricant employed for all castings was acetylene black.

Results

This work has adequately demonstrated the feasibility of machine casting semi-solid slurries of high temperature alloys. A total of 162

castings in the model high temperature bronze alloy have been made to date, Table I. Of these, castings #1-48 were used to develop and gain experience with the machine system, experimenting with process variables including runner design. Castings #49-89 were produced with more uniform conditions, with a gating design intermediate in the development of that shown in Figure 3. This batch of 40 castings was analyzed in the manner described in previous reports. This consists of (1) radiographic examination of casting soundness, (2) surface quality examination and (3) microstructural examination.

Generally, surface quality of these castings was good. The radiographs and associated microstructures of three castings are shown in Figure 4. These were cast in the liquid state (~100°C superheat), 0.43 and 0.52 volume fractions solid, respectively and show the relative radiographic ratings used in this analysis. This is the same as that employed in the previous report.[1]

The results of the radiographic analysis of castings #49-89 are summarized in Figure 5 in which each plotted point represents the average of at least 6 and generally 8 or 9 castings. This plot confirms previous work that increasing volume fraction solid produces sounder Thixocastings. It should be noted that these castings, made with slug temperatures typically about 960°C, were cast into dies operating at between 156-276°C. The good surface quality of the castings produced in such cold molds is further confirmation of the less turbulent die filling behavior of the semi-solid slurry.

A thin dendritically solidified skin exists on Thixocastings. The interior of these castings had a homogeneous distribution of primary solid particles, Figure 6. Particle distribution was also homogeneous throughout the runner and biscuit as can be seen in Figure 7. Here, the primary solid particles appear as both light and dark spots. A 100X photomicrograph of the runner of this casting is also shown in Figure 7. The primary solid particles are white, surrounded by a dendritic matrix. This casting was produced at a volume fraction solid of 0.43. The irregular primary solid particle shape is typical of all Thixocastings produced.

Subsequent to casting #89, further castings using the same gate geometry were made up to #118, at which point the final gate design (as shown in Figure 3) was adopted. All the castings #89-118 confirmed qualitatively the results shown in Figure 5. However, with the final runner design shown in Figure 3, and with added experience gained in operating the equipment castings of generally superior quality were obtained at a given fraction solid. Results of castings #118-169 are now being examined in a manner similar to that described above for castings #49-89.

Conclusions

1. A commercial horizontal cold chamber die casting machine and a reheating furnace have been coupled to form a Thixocasting system for casting reheated Rheocast slugs.

2. This Thixocasting system has been developed and operated to produce 162 castings of a simulated D.O.D. part in a model, copper base, high temperature alloy.
3. Results from this work confirm previous reports that castings with increasing internal soundness and good surface quality are produced as fraction solid of the charge material increase.
4. Cast parts exhibit essentially homogeneous distribution of primary solid particles enclosed in a thin fully dendritic skin.
5. Considerable working knowledge of the machine system and gating design has been gained from this work which will shortly be employed as work progresses to ferrous alloys.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, APPA Contract DAAG46-C-0110, 1 January 1974 - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts
2. R. G. Riek et al., "Machine Casting of a Partially Solidified High Copper Content Alloy", presented at T.A.F.S., St. Louis, Missouri, 1975.
3. R. G. Riek, et al., "Rheocasting of Ferrous Alloys", presented to S.D.C.E., Detroit, Michigan, 1975.

TABLE I

CASTING #	DIE TEMPERATURE °C	INJECTION PRESSURE p.s.i.	SLUG TEMPERATURE °C	REMARKS
1-48	320-360	6800-15,200	975-1020	used for system development, poor runner
49-89	164-260	15,200	960-1108 (9 slugs >1000°C)	first runner modification, used in analysis of casting quality
89-118	150-250	15,200	940-1018 (1 slug >1000°C)	
118-162	70-270	15,200	940-1000	final runner design

NOTE: Liquidus of the alloy is 999°C.

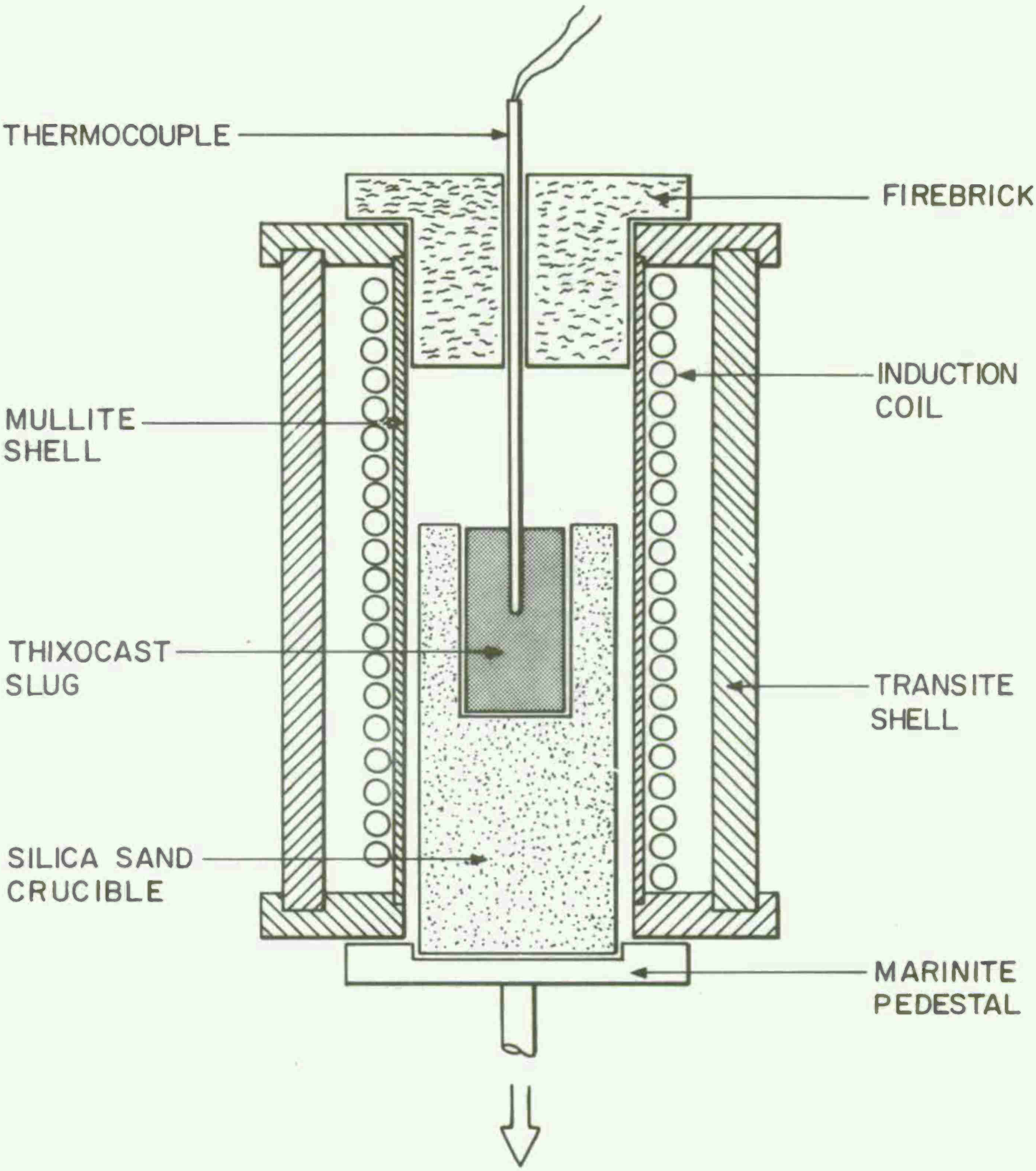
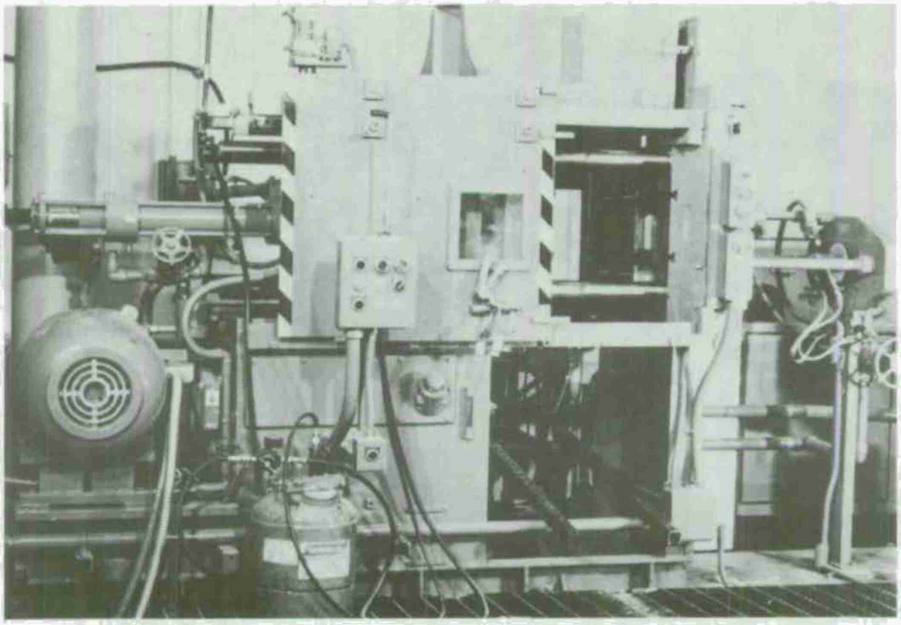


Figure 1. Schematic of reheat furnace.



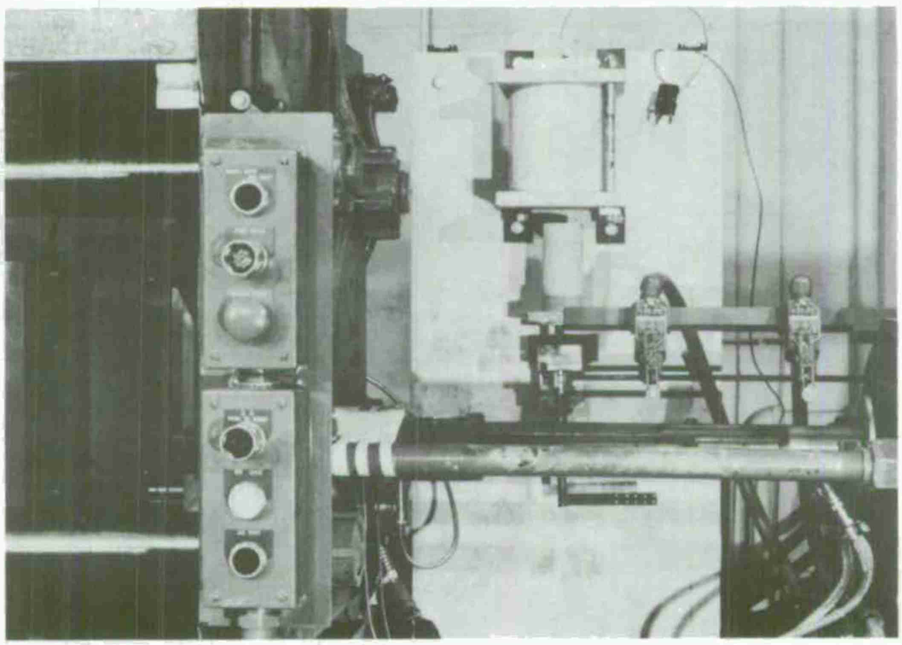


Figure 2. Photograph of high pressure die casting system. Top: overall view of B & T Greenlee, die casting machine. Bottom: close-up view of reheat furnace and shot chamber.

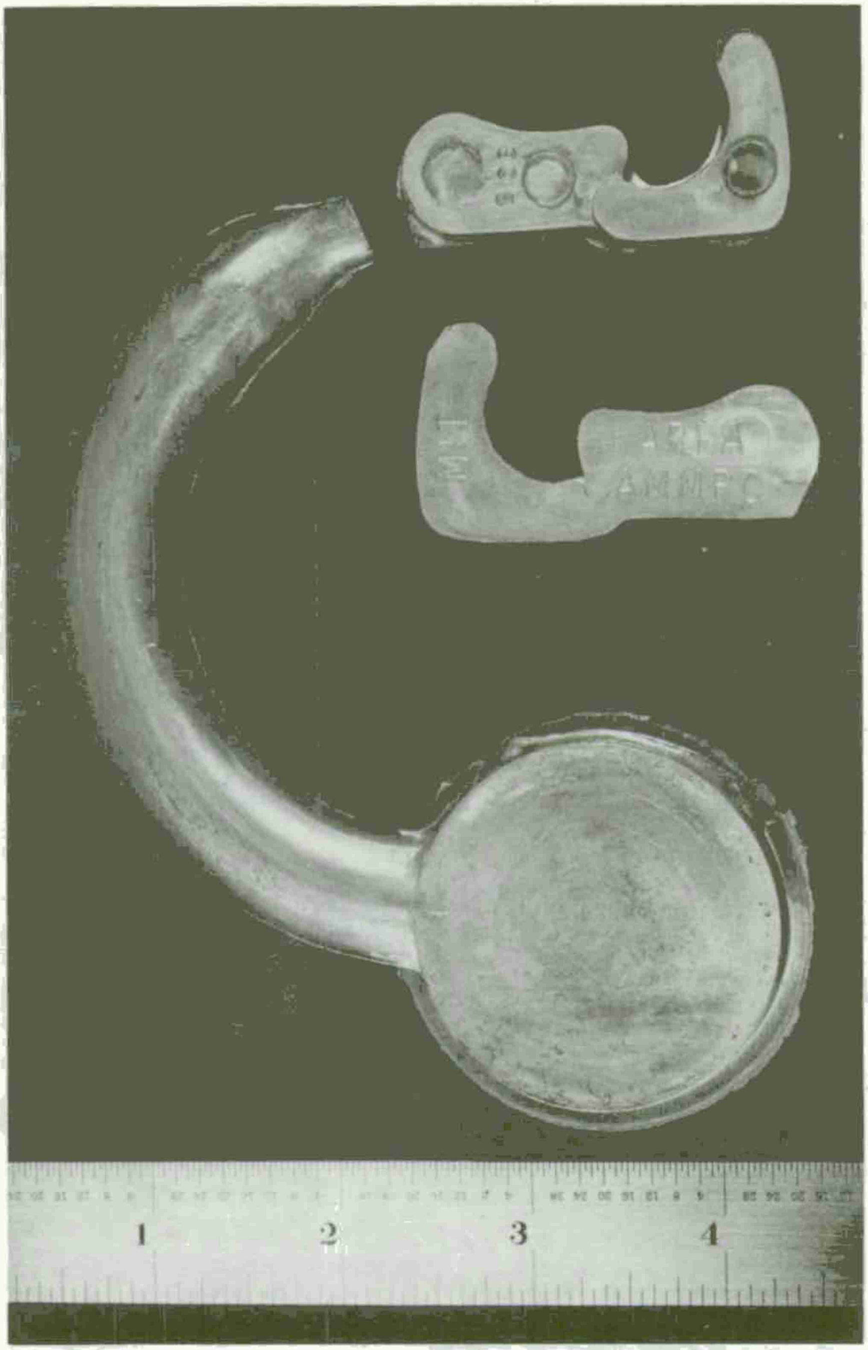


Figure 3. Photograph of modified M16 hammer casting showing the final gate geometry, 1X.

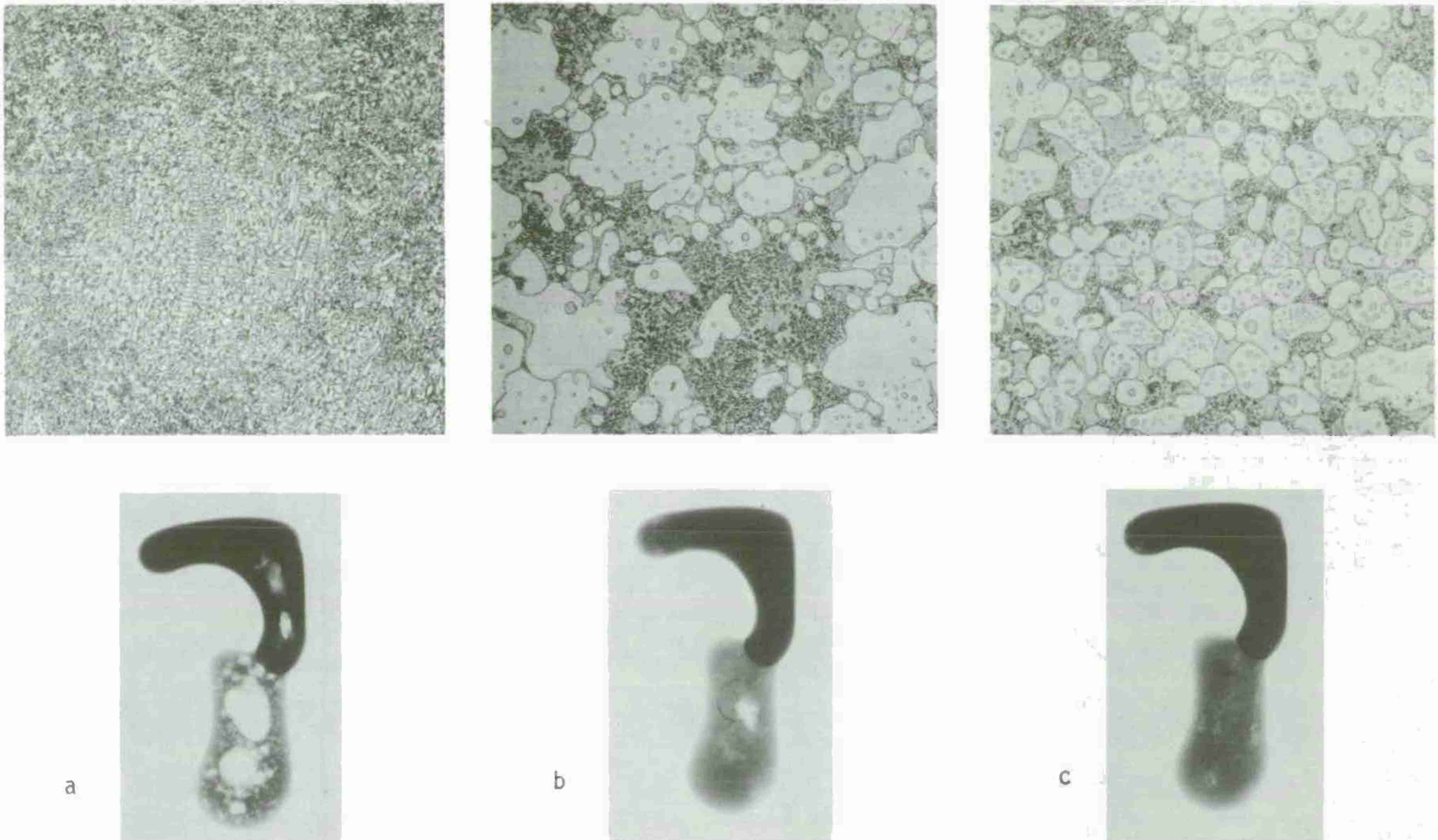


Figure 4. Radiographs and associated microstructures of conventionally cast and Thixocast copper base 905 alloy (88%Cu-10%Sn-2%Zn) produced in the B & T Greenlee die casting machine. (a) made from ~100°C superheated liquid. (b) and (c) from 0.43 and 0.52 volume fraction solid material, respectively. Radiographs represent radiographic ratings of 5, 2, and 1, 100X.

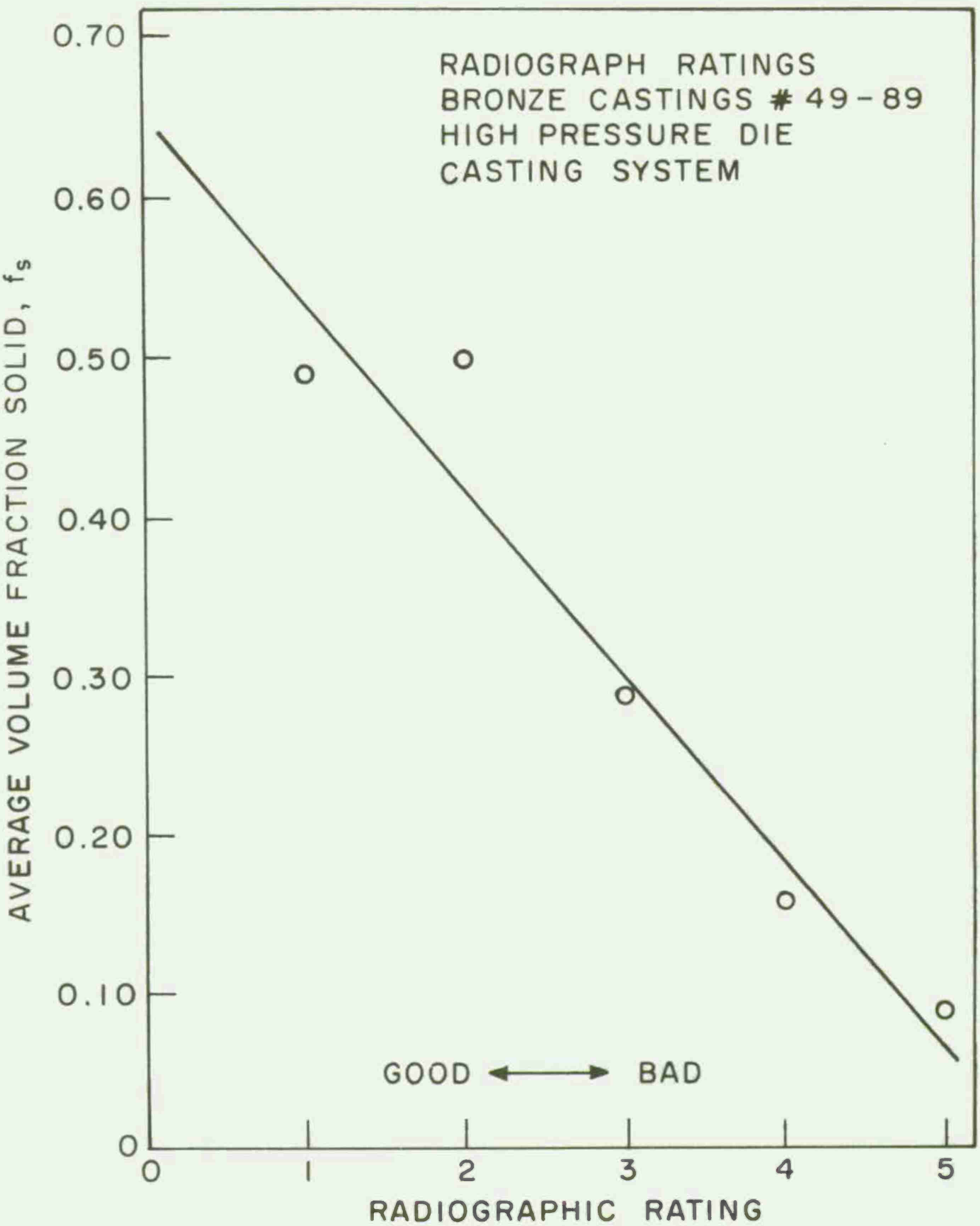


Figure 5. Relationship between volume fractions solid and radiographic ratings for castings #49-89. Each point represents average rating of at least 6 castings.

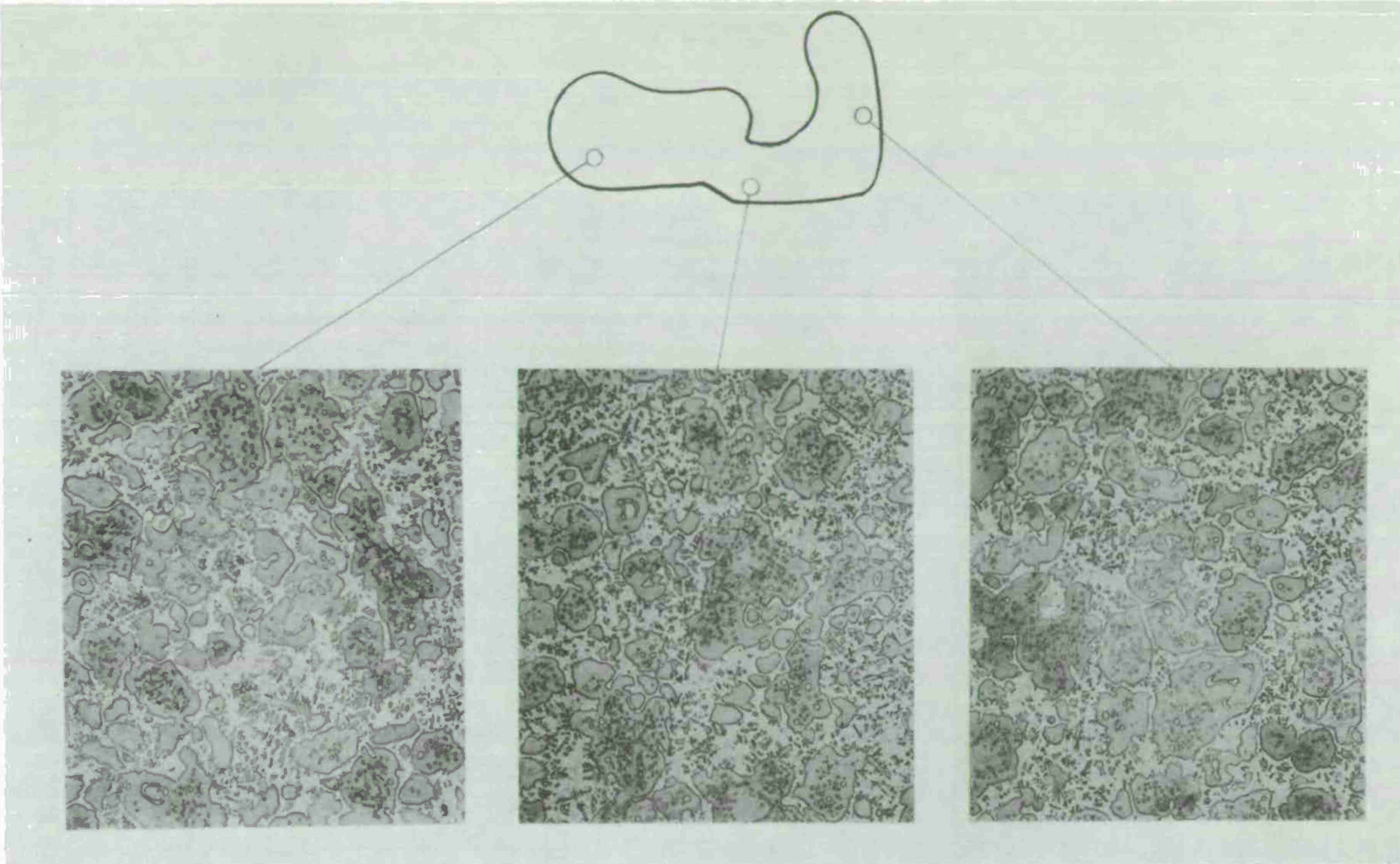
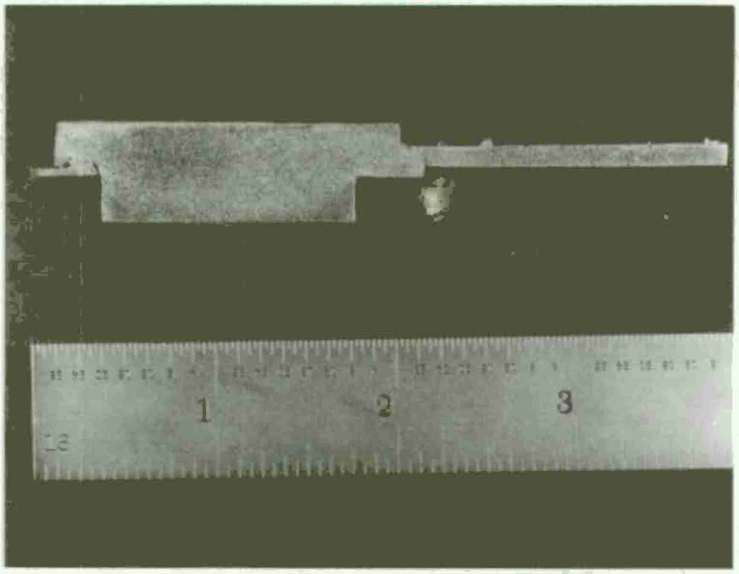


Figure 6. Microstructures of copper base 905 alloy (88%Cu-10%Sn-2%Zn) casting produced in B & T Greenlee die casting machine showing homogeneous distribution of primary solid particles, 100X



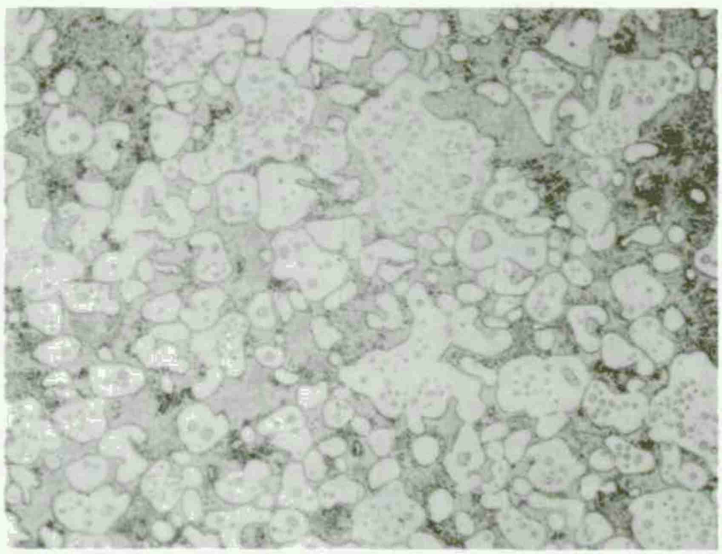


Figure 7. Photographs showing homogeneous distribution of primary solid particles in biscuit and runner. Copper base 905 alloy (88%Cu-10%Sn-2%Zn) cast at 0.43 volume fraction solid. Top: longitudinal section view of biscuit and runner. Primary solid particles appear as light and dark spots. Bottom: microstructure of runner, 100X.

CHAPTER III. THERMAL ANALYSIS OF THE MOLD

Summary

A program has been undertaken to assess and compare the die thermal behavior during the production of castings from fully liquid charge and semi-solid (Thixocast) charge. Internal die temperature measurements were made during casting of both liquid and semi-solid copper alloy 905. Computer calculations were made based on these experimental measurements to extrapolate the data to the die face. The calculations indicate that the use of semi-solid charge, as opposed to liquid charge, significantly reduces the die surface temperature, rate of heating, and maximum surface temperature gradient.

Introduction

One of the major contemplated advantages of using semi-solid charge material in machine casting is its expected beneficial effect on the thermal behavior of the mold during casting. This study is an attempt to determine the difference in die thermal behavior between casting with fully liquid superheated charge material and casting with partially solid (in this case Thixocast) charge material.

The study incorporates both experimental die temperature measurements and computer simulation. The stragegy of the approach has been to use the measured internal die temperatures to calibrate the computer program, which

in turn is employed to predict both the die surface temperature and surface thermal gradient. This procedure has been utilized to examine the die thermal behavior in both a low pressure laboratory casting machine and a high pressure commercial die casting machine. In what follows, each phase of the study will be presented separately.

Die Temperature Measurements

1. Temperature Measurement System

Miniature thermocouples were used to measure temperature near the casting-die interface in both the high and low pressure casting systems. The location of these couples with respect to each die cavity is shown in Figures 1 and 2. The distance from the bead of each to the cavity surface is .0139 inch. The detail of the thermocouple assembly is shown in Figures 1 and 2. Chromel/alumel wire (38 gauge) is sheathed in a 35 mil. two hole alumina protection tube which in turn is encased in a mild steel plug. The bead at the top of the couple is formed by spot welding the two wires and clipping off the excess.

The steel plug and thermocouple are fitted in a close tolerence hole drilled from the back of the die cavity. Contact between the thermocouple bead and the die is insured by adjusting the forcing bolt which applies pressure to the steel plug. The leads from the thermocouple are insulated with high temperature glass tape and are extended to the cold junction of the measurement system.

The cold junction is of standard construction. The output of the junction is fed into a two channel D.C. amplifier (gain = 100). The amplified signal is subsequently displayed in a Tektronix #533A dual trace and photographed to produce a permanent record of the temperature measurement.

2. Temperature Measurement Results

(a) Low Pressure System*

The first group of measurements were made during the casting of both liquid and semi-solid copper base alloy 905 (88%Cu-10%Sn-2%Zn) in the low pressure machine. The results of die temperature measurements at a location 0.0139 inch from the casting-die interface for two casting temperatures (T = 1100°C, f_s = 0.0; T = 970°C, f_s = 0.52) are shown in Figure 3. The general characteristics of each curve are similar--in both cases the die temperature heats rapidly for 0.2 - 0.3 seconds. At that time, however, the temperature of the die begins to decrease gradually. In comparing the die thermal response for fully liquid and semi-solid bronze 905, we find that the maximum temperatures attained are 574°C and 507°C, respectively. Because the initial die temperature (before casting) is 420°C in each case, the ratio of the temperature rise for the two castings is 1.7. The initial rates of heating for liquid and semi-solid bronze are 2000°C/sec. and 880°C/sec. (ratio 2.3), respectively.

---

*The "low pressure die casting machine" used for this portion of the study is the "homemade" machine described in the previous report,[1] and illustrated in Figure 2, Chapter II of that report.

(b) High Pressure System*

Die temperature measurements were made during the production of bronze 905 alloy castings, using both liquid and semi-solid charge material, in the high pressure die casting machine. The thermocouple was located 0.0139 inch from the casting-die interface.

The die temperature measured during the casting of superheated liquid, $T_o = 1100°C$, and semi-solid $T_o = 960°C$, $f_s = 0.57$, bronze 905 are shown in Figure 4. For short times ($t<0.15$ sec.), each temperature plot is characterized by a large amount of rapid variation. During this period the maximum temperatures attained are 645°C and 315°C for the casting of liquid and semi-solid bronze 905, respectively. After this period, however, the die temperature for each case rises to a peak and then falls. After approximately 0.5 seconds, the die temperature at the thermocouple location levels and maintains a constant value. The initial rates of die heating are 2.47×10^4°C/sec. and 8.25×10^3°C/sec. (ratio = 2.99) for the fully liquid and semi-solid castings, respectively. The die temperatures at 0.60 seconds are 400°C and 270°C for the same two castings. The ratio of the corresponding temperature rise above ambient is 2.08.

Die Heat Flow Simulation

1. Computer Model

A computer program was developed to simulate heat flow within the die of a die casting machine. It is briefly discussed in the previous report.[1]

*The "high pressure machine" used for this portion of the study is the commercial machine described in Chapter II of this report, and pictured in Figure 2, Chapter II.

The computer program employs a finite one-dimentional heat flow model which is solved using a forward difference technique. The geometry and dimensions of the model are shown in Figure 5. The physical assumptions made are:

1. the die is filled instantaneously,
2. the die and casting comprise an adiabatic system with no heat losses to the surroundings,
3. the die is initially at uniform temperatures and undergoes no solid state transformations upon heating,
4. the physical properties of the liquid metal are independent of temperature,
5. the solidifying casting is sound (has no porosity),
6. heat flow at the die metal interface is characterized by a surface heat transfer coefficient which is a simple function of time.

The mathematical problem can be represented by the following equation:

$$k \frac{\partial^2 T}{\partial x^2} = \frac{\partial H}{\partial t}$$

where T and H are the temperature and enthalpy, respectively, at position x and k represents the thermal conductivity. Transcribing this equation to finite difference form we obtain the following equation and boundary conditions:

$$H_i\ (t + \Delta t) = H_i\ (t) + \frac{k}{\rho(\Delta x)^2}\ [T_{i+1}\ (t) - 2T_i(t) + T_{i-1}(t)]\ \Delta t$$

(1) $T_1(t) = T_2(t)$

(2) $T_{25}(t) = T_{24}(t)$

(3) $$H_5(t+\Delta t) = H_5(t) + \frac{2}{\rho\Delta x}\left[\frac{kT_4(t)}{\Delta x} - \left(\frac{k}{\Delta x} + h\right) T_5(t) + hT_6(t)\right]$$

$$H_6(t+\Delta t) = H_6(t) + \frac{2}{\rho\Delta x}\left[\frac{kT_7(t)}{\Delta x} - \left(\frac{k}{\Delta x} + h\right) T_6(t) + hT_5(t)\right]$$

(4) $t = 0,\ 1 \le i \le 5;\ T_i = T_o$

(5) $t = 0,\ 6 \le i \le 25;\ T_i = T_D$

Where T_o and T_D represent the initial charge and die temperatures respectively, and h equals the surface heat transfer coefficient. The subscripts on temperature and enthalpy represent specific nodes within the computational mesh. These equations are applied respectively at each node of the computer model, Figure 5, thus producing the variation of temperature throughout the die as a function of time.

2. Computer Results

The thermal computer program was implemented to simulate heat flow within the dies of the low and high pressure casting systems. The value of the surface heat transfer coefficient, h, was adjusted to provide agreement between the output of the computer program and the experimentally measured die temperatures previously reported. This approach was employed for fully liquid and semi-solid copper base alloy 905 castings produced in both casting systems.

The experimentally measured die temperature curves (for both high and low pressure systems) each exhibit similar characteristics, Figures 3 and 4,

as previously described. Initially, the dies heat up rapidly reaching a maximum temperature between 0.05 and 0.3 seconds. However, at this time the die temperature either levels or drops. In order to replicate these characteristics with the computer program, the value of the surface heat transfer coefficient, h, has been abruptly lowered during the casting cycle.

(a) Low Pressure System

The experimentally measured and calculated die temperatures at a location 0.0139 inch from the casting-die interface for fully liquid (T = 1100°C) and semi-solid (T = 970°C, f_s = 0.53) copper base alloy 905 castings produced in the low pressure casting machine are compared in Figure 3. The initial values of h employed for calculation are 0.30 cal/cm^2 °C/sec. and 0.15 cal/cm^2 °C/sec. for the liquid and semi-solid castings, respectively. The transition to the final value of h (0.08 cal/cm^2 °C/sec.) occurs at 0.25 and 0.15 seconds, respectively. Thus the initial value of the surface heat transfer coefficient is both higher and applicable for longer times when castings are produced from liquid charge material. Using these values of h and the transition times, the measured and calculated curves agree well for both liquid and semi-solid castings, particularly for short times. For longer times, the general behavior of the measured and calculated curves is similar.

(b) High Pressure System

It is more difficult to simulate heat flow within the dies of the high pressure die casting machine during the casting of fully liquid and semi-solid bronze alloy 905, owing principally to the rapid temperature fluctuations which occur at short times, Figure 4. However, it was possible to study isolated sections of measured temperature curves and simulate heat flow during these sections separately. For example, the initial temperature rise for fully liquid (T = 1100°C) and semi-solid (T = 960°C, f_s = 0.57) bronze 905, Figure 4, corresponds to values of h equal to 10.0 cal/cm^2 °C/sec. and 3.0 cal/cm^2 °C/sec., respectively. These h values are significantly higher than those recorded for the low pressure casting machine. However, examination of the experimentally measured temperatures for times greater than 0.1 seconds (i.e., ignoring the period of rapid temperature fluctuation) indicates that the initial values of the surface heat transfer coefficient are 3.0 cal/cm^2 °C/sec. and 0.15 cal/cm^2 °C/sec. for fully liquid and semi-solid bronze alloy 905 castings, respectively. For the fully liquid casting the value of h changes to 0.04 cal/cm^2 °C/sec. at 0.15 seconds; whereas for the semi-solid casting the value of h changes to 0.08 cal/cm^2 °C/sec. at 0.35 seconds. Using these h values and transition times yields good agreement between the measured and calculated curves through ignoring the period of rapid temperature fluctuation.

Temperature Prediction at the Casting-Die Interface

The main objective of the thermal computer program was to predict the die surface temperature and surface thermal gradient. The value of the surface heat transfer coefficient for these computer runs was determined by matching the measured and calculated temperatures within the die as described above. Simulations were conducted for copper base alloy 905 and eutectic cast iron in both the high and low pressure casting systems.

(a) Low Pressure System

The predicted die surface temperatures produced during the low pressure casting of fully liquid (T = 1100°C) and semi-solid (T = 970°C, f_s = 0.53) bronze alloy 905 are shown in Figure 6. The maximum temperatures attained are 614°C and 513°C, respectively, yielding a ratio of temperature rise equal to 2.09. The initial rates of die surface temperature increase for the two castings are 2600°C/sec. and 1080°C/sec., respectively. The initial die thermal gradients at the casting-die interface are 1300°C/cm and 590°C/cm for fully liquid and semi-solid bronze, respectively.

(b) High Pressure System

The computer simulated die surface temperatures for fully liquid and semi-solid copper base alloy 905 castings made in the high pressure die casting machine are plotted in Figure 7. The initial period of rapid temperature fluctuation, Figure 4, has been ignored as described earlier. In the fully liquid simulation, the

initial value of h was 3.0 cal/cm^2 °C/sec. and was lowered to 0.04 cal/cm^2 °C/sec. at 0.05 seconds. On the other hand, for the simulation of semi-solid castings, the initial value of h was 0.15 changing to 0.08 at 0.25 seconds.

For copper base alloy 905, the computer simulation indicates that the die surface temperature is lowered significantly when semi-solid charge material is die cast in the high pressure casting system. The maximum die surface temperatures attained are 800°C and 315°C for fully liquid and semi-solid charge material, respectively. As the initial die temperature was 150°C, the heating of the die surface was reduced by a factor of 4 for the semi-solid material as compared to the fully liquid charge.

The initial rates of temperature increase are 11,000°C/sec. and 1,600°C/sec. for the fully liquid and semi-solid material, respectively. This is a reduction by a factor of 7 for the semi-solid material. The values of the initial die thermal gradient at the casting-die interface are 5,640°C/cm and 718°C/cm respectively, a reduction by a factor of 8 for the semi-solid material.

Discussion

Die deterioration is a major limitation confronted when attempts are made to die cast fully liquid high melting temperature alloys. Two prevalent modes of degradation are die cracking and chemical and mechanical erosion; each phenomena being governed by the behavior of heat flow

within the die during filling. Severe thermal gradients and rapid surface heating within the die at the casting-die interface are believed to cause thermal cracking whereas high surface temperatures lead to surface erosion.

In this study, both experimental measurements and computer simulation indicate that during the die casting of semi-solid alloys (Thixocasting) the die temperature, rate of temperature increase, and thermal gradient at the die face are dramatically lower than when fully liquid alloys are die cast. For example, in the high pressure system measured temperature rise is reduced by a factor of 4, rate of temperature rise is reduced by a factor of 7, and thermal gradient at the die face is reduced by a factor of 8 when casting a semi-solid charge.

In order to provide good agreement between the measured and calculated die temperatures it was necessary to change the values of the surface heat transfer coefficient, h, during computer simulations. The abrupt change in this value corresponded approximately to the die fill time, t ~0.1 seconds, determined by measuring the plunger velocity Figure 3. The two values of the surface heat transfer coefficient, h_i and h_f, denote the initial and final heat transfer coefficients.

In the low pressure (laboratory) casting apparatus the calculated h_i and h_f values were in the range of 0.10 to 0.30 and 0.06 to 0.08 cal/°C/sec. cm^2, respectively, for both the liquid (superheated 100°C) and semi-solid (volume fraction solid ~0.5) charge bronze, Figure 3. The

variation in the values of h_i and h_f between the castings produced with the all liquid and semi-solid charge was much more pronounced in the high pressure commercial die casting machine. For fully liquid bronze $h_i = 3.0$, $h_f = 0.04$; for semi-solid bronze $h_i = 0.15$ and $h_f = 0.08$ cal °C/sec. cm^2.

This thermal study is continuing. The emphasis will be on refining both experimental techniques and the mathematical model to better understand the details of heat flow behavior in the die casting of both liquid and semi-solid alloys.

Conclusions

1. Both experimental measurements and computer simulation indicate that during the die casting of semi-solid alloys the die temperatures, rate of surface heating and surface temperature gradients are dramatically lower than when fully liquid superheated alloys are cast.
2. Correlation of experimentally measured die temperatures with computer simulation enabled prediction of the value of the surface heat transfer coefficient. An abrupt change in the surface heat transfer coefficient occurs at approximately the same time that the die cavity is completely filled.
3. In the low pressure (laboratory) casting apparatus the calculated initial and final heat transfer coefficients were in the range of 0.10 to 0.30 and 0.06 to 0.08 cal/°C/sec. cm^2, respectively, for both the liquid and semi-solid charge copper-base alloy 905.

4. In the high pressure commercial die casting machine initial and final heat transfer coefficients for the superheated (100°C) copper-base 905 alloy were 3.0 and 0.04 cal/°C/sec. cm^2, respectively. The corresponding values for the semi-solid (volume fraction solid ~0.5) were 0.15 and 0.08 cal/°C/sec. cm^2. respectively.

5. Computer calculations based on experiment show that when a semi-solid charge material of copper-base alloy 905 is used,die surface temperature, rate of surface heating, and maximum surface temperature gradient are all drastically reduced. In the high pressure commercial die casting machine the predicted maximum die surface heating for conditions studied was 650°C and 165°C for the liquid and semi-solid (Thixocast) material, respectively. This is a reduction by a factor of 4 for the semi-solid material. Initial surface heating rates were 11,000°C/sec. and 1,600°C/sec. respectively, a reduction by a factor of 7 for the semi-solid material. Initial thermal gradients at the liquid-solid interface were 5,640°C/cm and 718°C/cm, a reduction by a factor of 8 for the semi-solid material.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January 1974 - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

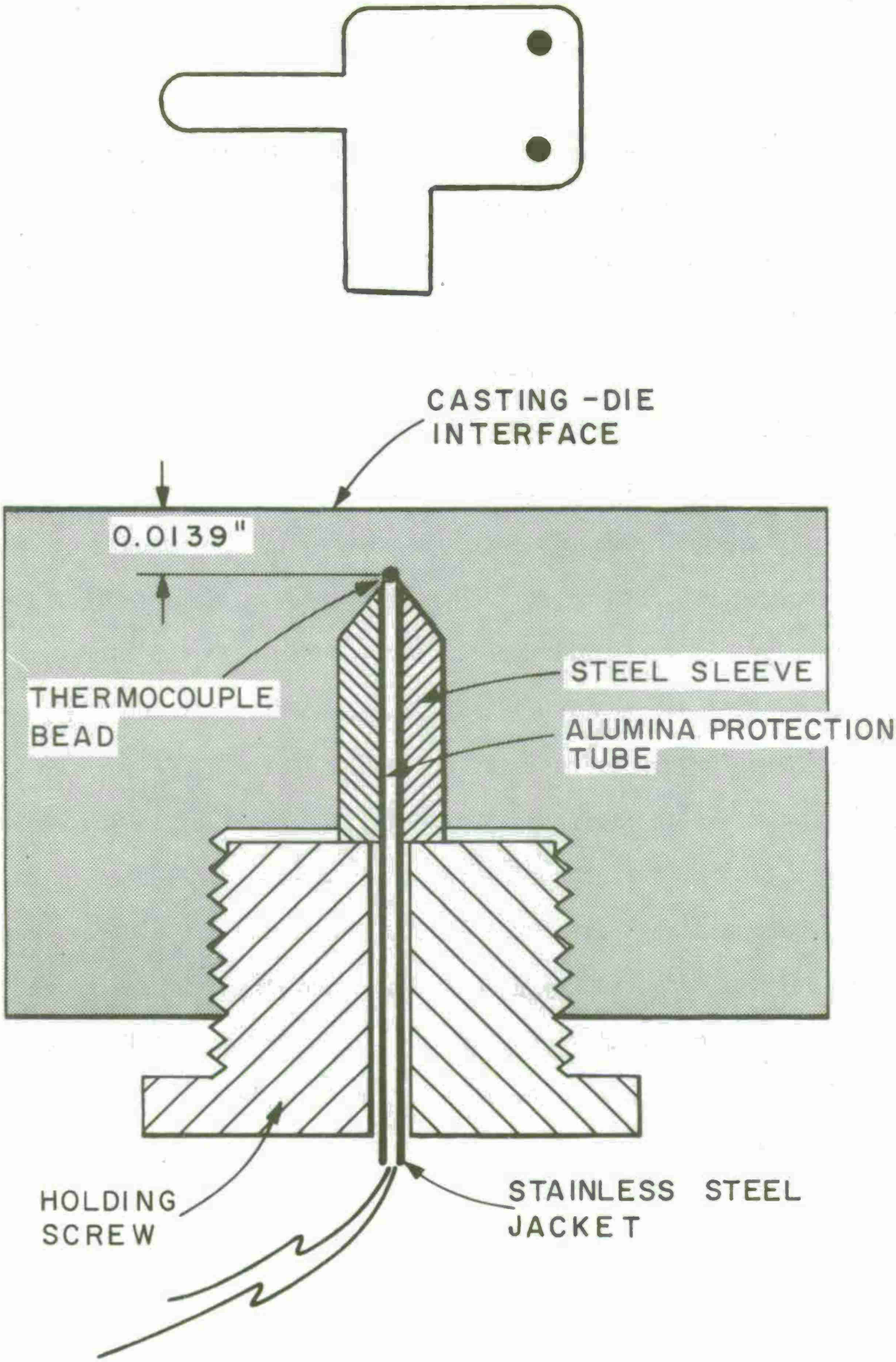


Figure 1. Schematic of thermocouple assembly in the low pressure die casting machine. Figure on top shows position of the thermocouple in the die cavity.

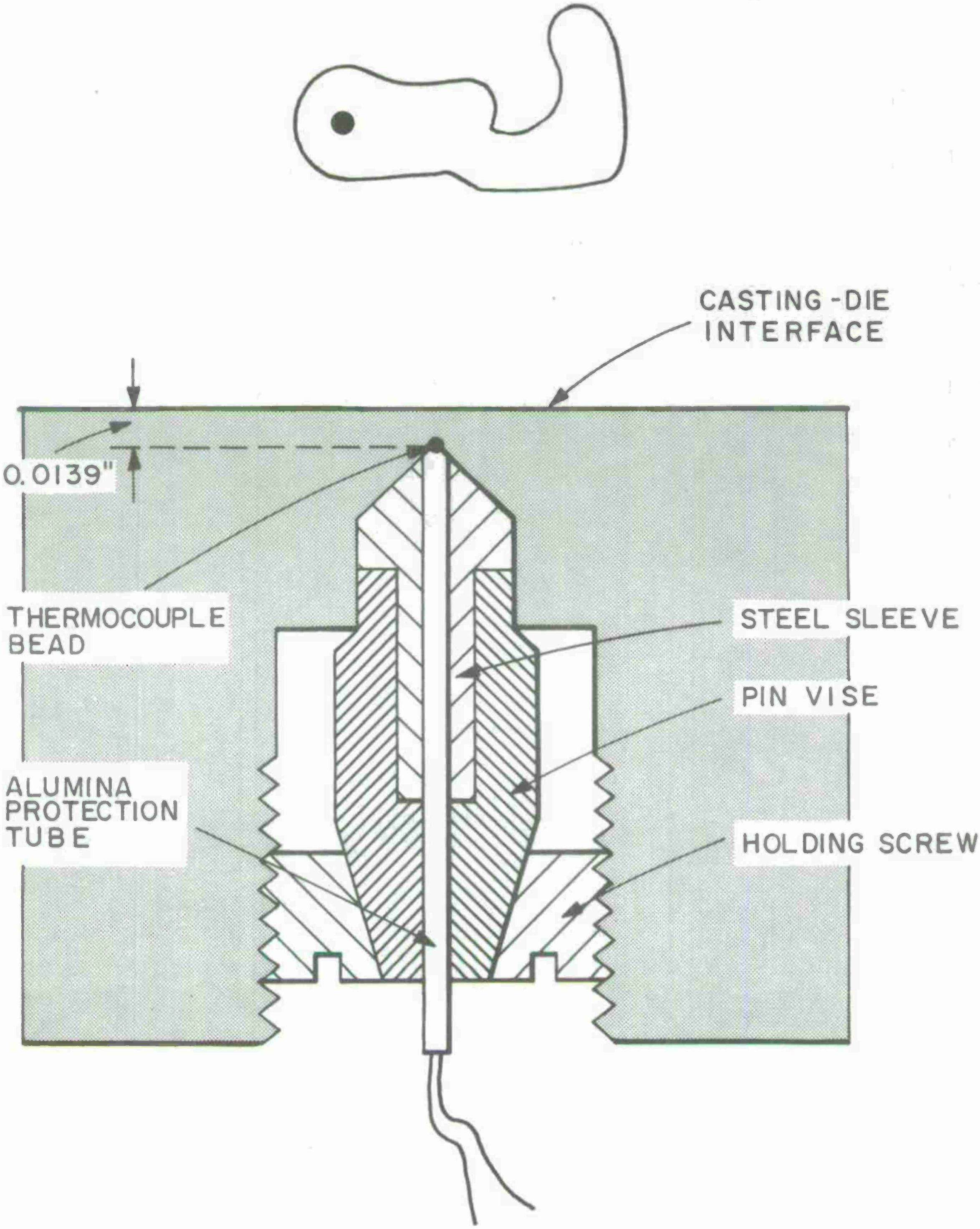


Figure 2. Schematic of thermocouple assembly in the high pressure die casting machine. Figure on top shows position of the thermocouple in the die cavity.

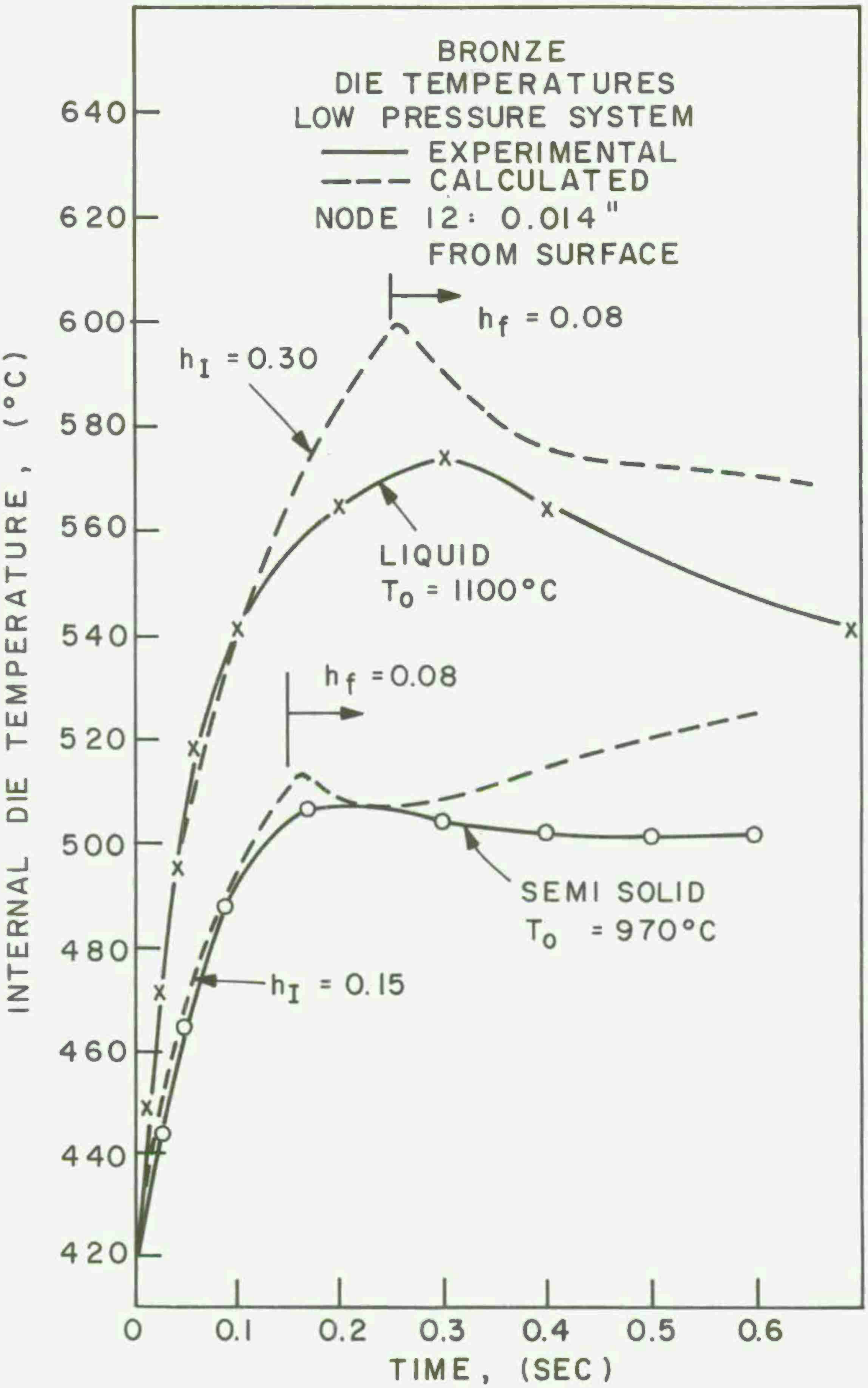


Figure 3. Measured die temperature during the casting of liquid and semi-solid copper base alloy 905, 88%Cu-10%Sn-2%Zn, in the low pressure die casting machine. Thermocouple was located at node 12, 0.0139 inch from casting-die interface. Dotted lines represent the calculated temperature variation produced by computer simulation.

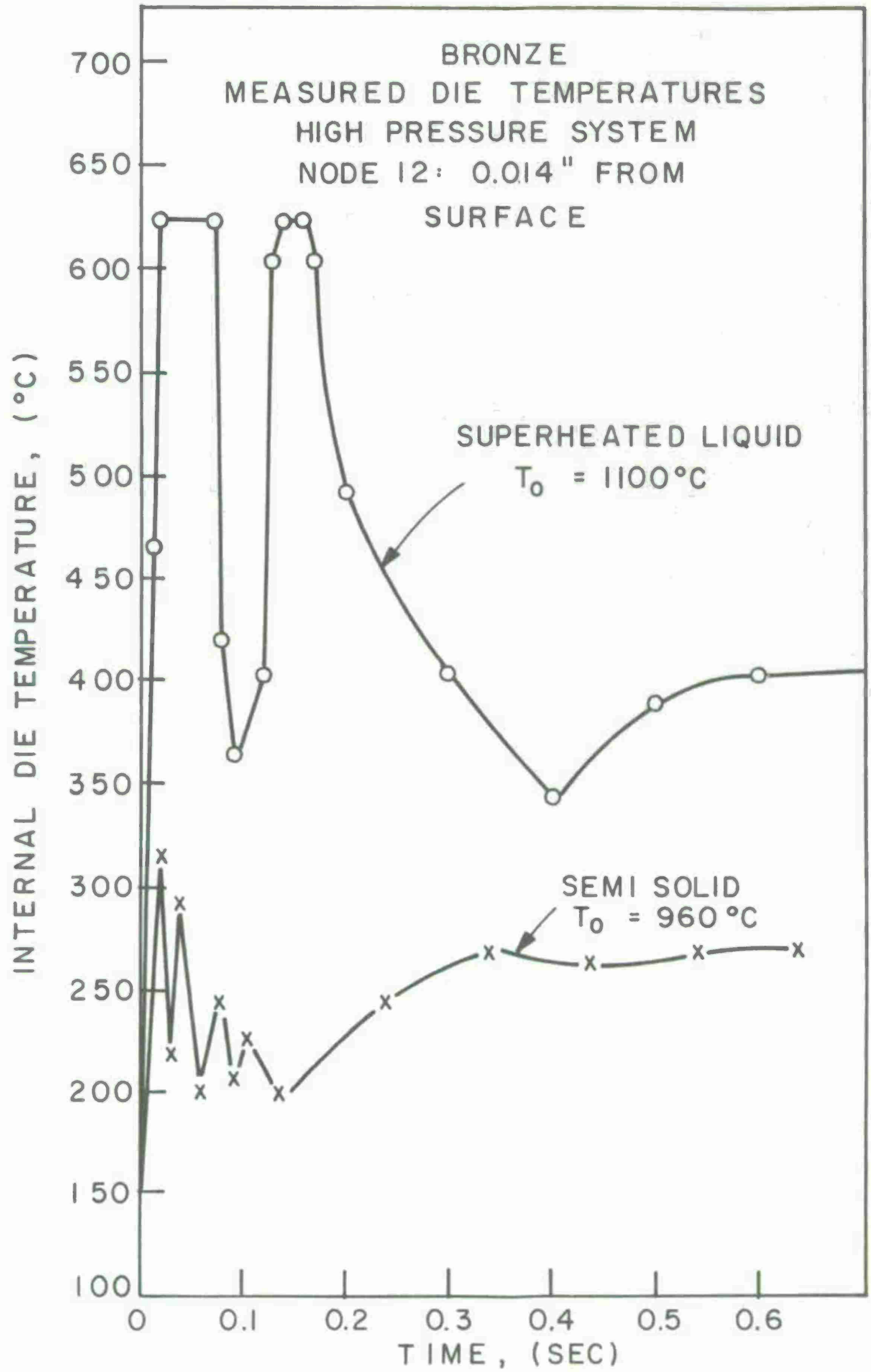


Figure 4. Measured internal die temperatures during the casting of liquid and semi-solid copper base alloy 905, 88%Cu-10%Sn, 2%Zn, in the high pressure die casting machine. Thermocouple located at node 12, 0.0139 inch from the casting-die interface.

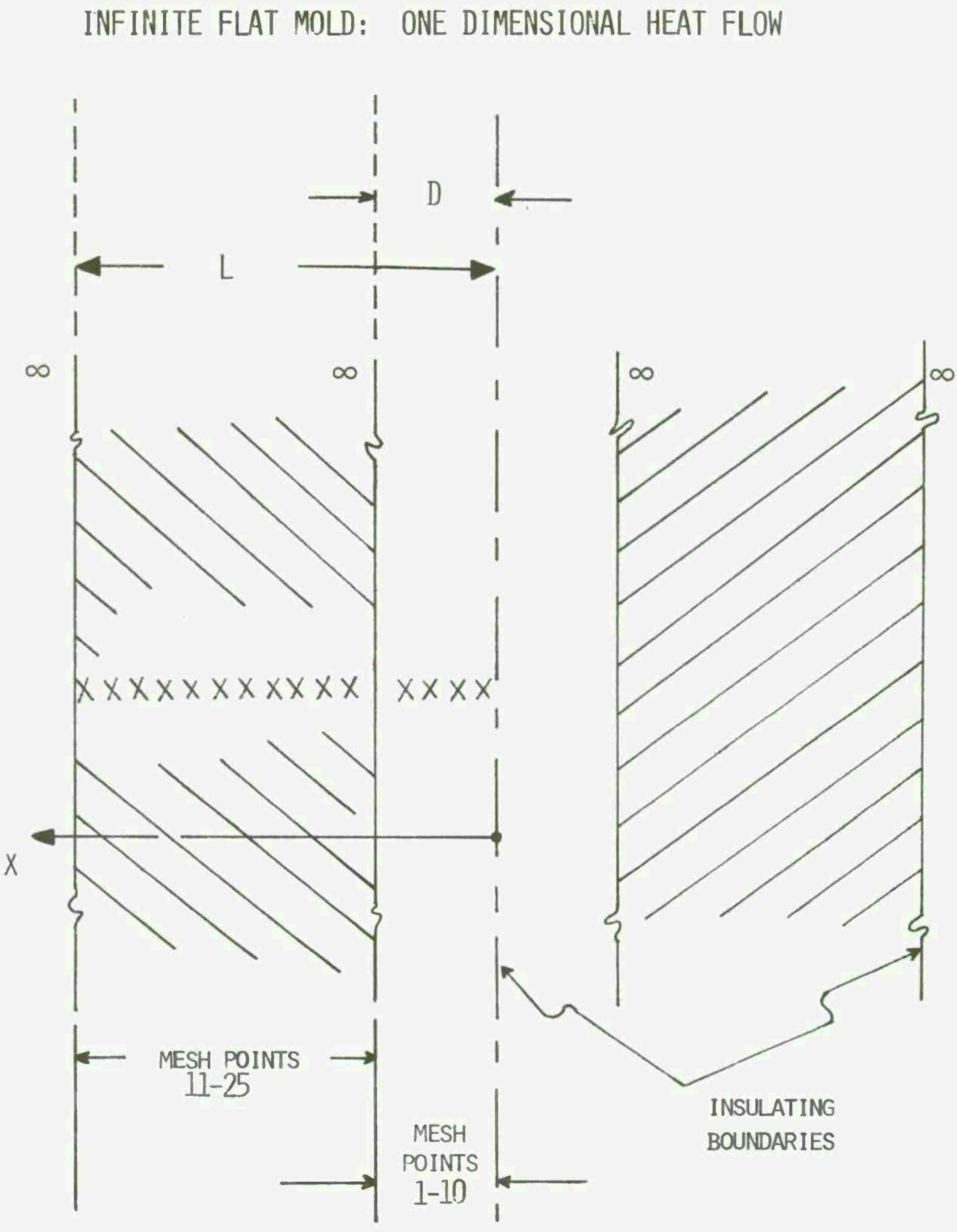


Figure 5. Schematic diagram showing the one dimensional computer model.

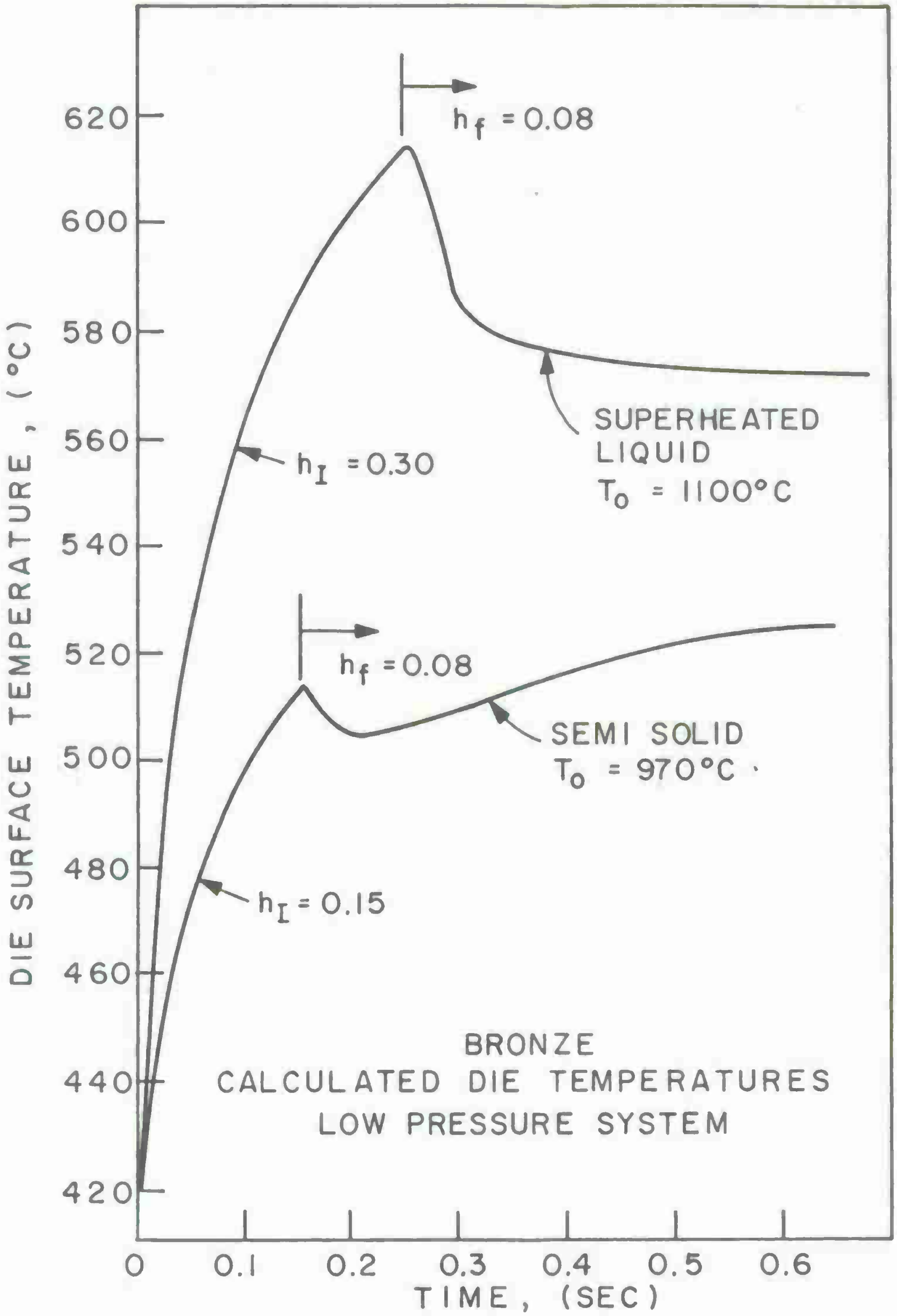


Figure 6. Computer simulated die surface temperatures as a function of time for the liquid and semi-solid copper base alloy 905, 88%Cu-10%Sn-2%Zn, cast in the low pressure system.

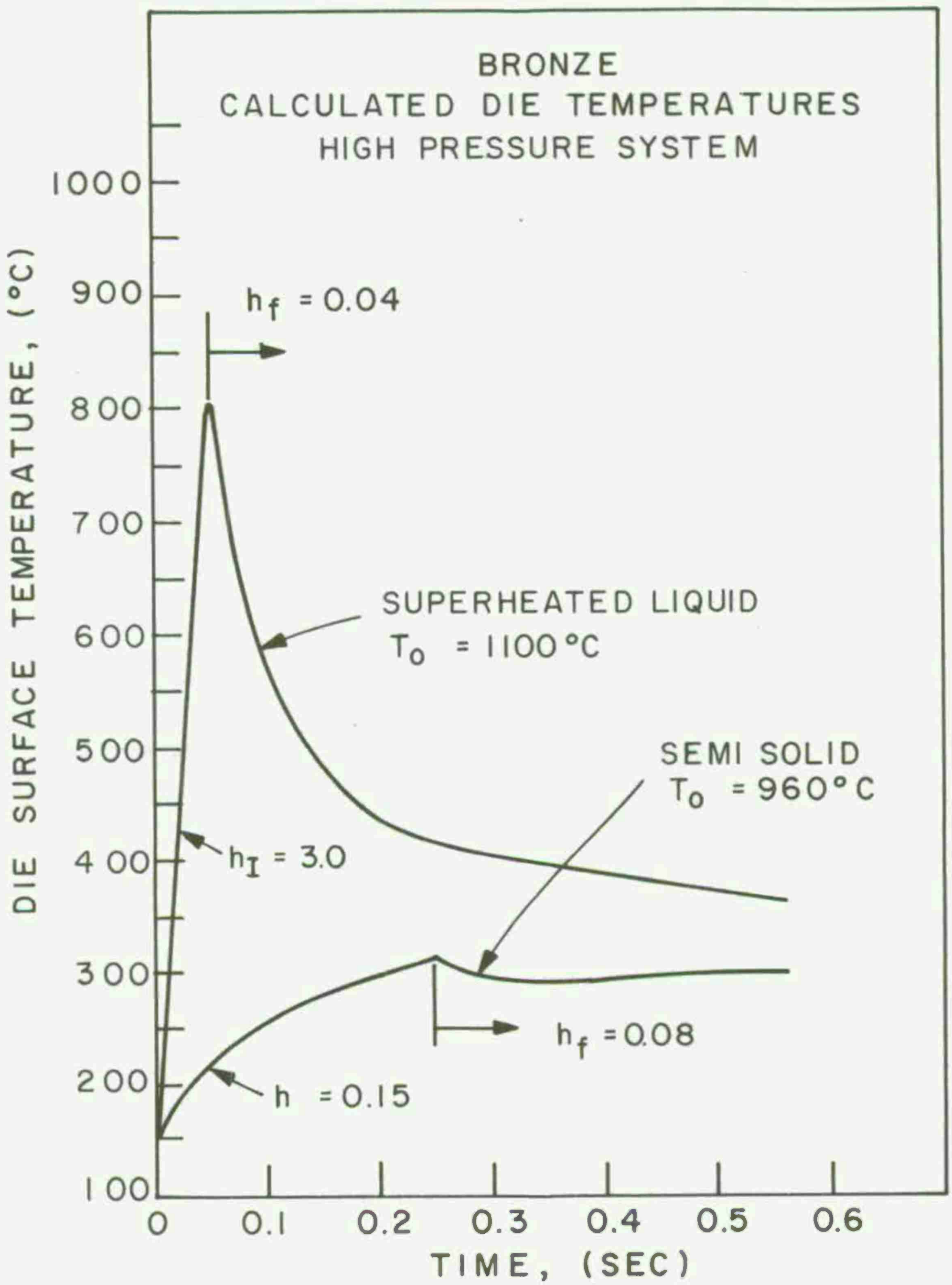


Figure 7. Die surface temperature as a function of time for liquid and semi-solid copper base alloy 905, 88%Cu-10%Sn-2%Zn, cast in the high pressure die casting machine.

CHAPTER IV. STRUCTURE OF Sn-Pb SLURRIES

Summary

Tin-lead slurries from the low temperature Rheocaster were examined metallographically. Process variables during the production of the slurries were the cooling rate, shear rate, volume fraction solid, and composition. Primary particle size decreased markedly with increasing cooling rate, in the range of 0.800°C/min.$^{-1}$ and to a lesser extent with increasing shear rate in the range of 0-1000 sec.$^{-1}$ Primary particle size increased with fraction solid. Particle sizes obtained were in the range of 60-250μm.

Production of pure Sn, Sn-Pb eutectic and near eutectic slurries has confirmed the feasibility of Rheocasting narrow freezing range or isothermal freezing metals and alloys. Slurries of alloys at or near the eutectic composition contain both lead-rich and tin-rich phases. Primary tin-rich particles retain the approximate size and shape they had at the time the eutectic liquid composition was reached.

Introduction

The low temperature continuous Rheocaster has been described in detail in earlier reports.[1,2] Superheated liquid metal or alloy is allowed to flow from an upper reservoir chamber through a cylindrical mixing chamber. Within the mixing chamber a concentric, rotating, shaft produces shear within the metal or alloy as it is cooled below

its liquidus temperature. The structure modification of the fraction solid forming within the mixing chamber caused by the shearing results in the alloy exiting the bottom of the mixing chamber as a semi-solid slurry. This study has consisted of an investigation, using the model Sn-Pb low temperature alloy of the effects of the principle process variables upon the Rheocast structure.

Those process variables considered are the cooling rate within the mixing chamber, shear rate and volume fraction solid and composition. Of these process variables two, the volume fraction solid and composition, are not influenced by machine design. Furthermore, the apparatus as originally designed and described[1,2] permitted large variation in shear rate (0-100 $sec.^{-1}$). However, the cooling rate within the mixing chamber was not initially very flexible.

The cooling rate of the metal or alloy as it flows through the mixing chamber is proportional to both the temperature gradient along the length of the chamber and to the flow rate of the alloy through the chamber. In order to increase both of these factors, the rate of heat removal from the mixing chamber was increased by modification of the apparatus.

Apparatus Modifications

Three types of cooling systems were used, the first two of which were described in earlier reports.[1,2] The first is a shroud surrounding the mixing chamber. Compressed air is blown through the shroud cooling

the entire length of the mixing chamber. This system can produce cooling rates of up to 100°C/min. with Sn15wt% alloy.

The second system is a one inch aluminum ring which slips over the mixing chamber and which is cooled by water flowing through an internal channel. Cooling in this design is limited by the poor thermal contact between the outside of the mixing chamber and the inside of the ring. Nevertheless, cooling rates up to 400°C/min. can be obtained.

The third and new system is a one inch aluminum ring with a groove machined in its inside diameter. A water channel thus formed by the inside diameter of the aluminum ring and the outside of the mixing chamber is sealed by "O"-rings. This places the cooling water in direct contact with the outside of the mixing chamber. Available heat removal rates with this system are more than sufficient and in this case the maximum slurry cooling rate is limited by the flow rate of metal slurry through the mixing chamber. Maximum cooling rate obtained thus far was approximately 800°C/min.

Experimental Procedure

The Rheocaster was heated to a temperature above the liquidus of the alloy being used, and the rotor speed was set to give the desired shear rate. The mixing tube was then cooled. When the desired fraction solid at the exit port was reached, the coolant flow and slurry flow were adjusted to maintain a constant fraction solid. Before samples were

taken, the machine was allowed to run long enough to insure steady conditions. Samples were quenched in ice water as they fell from the exit port. Each sample was taken for a measured period of time and the sample weighed to determine the flow rate. The cooling rate for the sample as it flowed through the mixing tube was calculated from the temperature gradient, the flow rate, and the volume of the mixing tube.

Tin-15wt%Pb alloy slurries were produced with cooling rates of from 20 to 800°C/min. and shear rates of from 100 to 1000 sec.$^{-1}$.

Slurries were also produced from pure tin, Sn-5wt%Pb, Sn-25wt%Pb, Sn-35wt%Pb and Sn-Pb eutectic (38wt%Pb).

Results

Sn-15wt%Pb Alloy

The effect of cooling rate, shear rate, and fraction solid on primary particle morphology is shown in Figures 1 - 5. Figure 1 shows how particle size decreases with increasing cooling rate up to 1000°C/min. The change is most marked for cooling rates below 200°C/min. Figure 2 shows representative photomicrographs of structures produced at these different cooling rates. The shape of the particles is seen to change little over this range of cooling rates.

In general, primary particle size decreases with increasing shear rate as shown in Figure 3 for shear rates up to 1000 sec.$^{-1}$. The change in size due to change in shear rate over this range is much less significant than that due to change in cooling rate. Furthermore, as Figure 3

shows, the effect of shear rate decreases with increasing cooling rate. As shown in Figures 4 and 5, particle size increases with increasing fraction solid at all cooling rates.

Other Alloys

Slurries were produced from pure Sn and from Sn-Pb alloys ranging in Pb up to the eutectic. Alloys with Pb concentration less than 15 percent produced slurries similar to the Sn-15wt%Pb slurries discussed above.

For alloys near the eutectic, the eutectic temperature was reached at a low fraction solid of primary tin-rich phase. With continued cooling, structures such as those in Figure 6 were produced containing both eutectic phases. Since eutectic liquid solidifies isothermally, cooling rates as used for the Sn-15wt%Pb alloy are not applicable. However, the heat removal and solidification rates for the structures in Figures 6a, b and c, correspond to Sn-15wt%Pb cooling rates of approximately 20, 100 and 250°C/min., respectively. As Figure 6 shows, the structures obtained when the eutectic is formed within the mixing chamber can be either radial lamellar growth as Figure 6c or as equiaxed particles of Pb-rich phase associated with Sn-rich particles as shown in Figure 6b. This phenomena is currently under further investigation.

Before the eutectic begins to solidify, the primary tin-rich particles behave like the particles in the Sn-15wt%Pb alloy. However, when the second phase begins to solidify the original primary particles cease

growing as shown in Figure 7. Thus the primary particle size is constant with increasing fraction solid, at the size dictated by the shear rate and cooling rate experienced in pre-eutectic freezing.

Conclusions

For Sn-Pb Alloys

1. Primary particle size increases with increasing fraction solid and decreasing cooling rate.
2. Primary particle size increases only slightly with decreasing shear rate and only at low cooling rates.
3. The continuous slurry producer can be used with alloys that freeze isothermally.
4. When the eutectic temperature is reached, primary tin-rich particle growth ceases and the two eutectic phases solidify as a distinct structure.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0010, 1 January - 30 December 1973, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.
2. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0010, 1 January - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

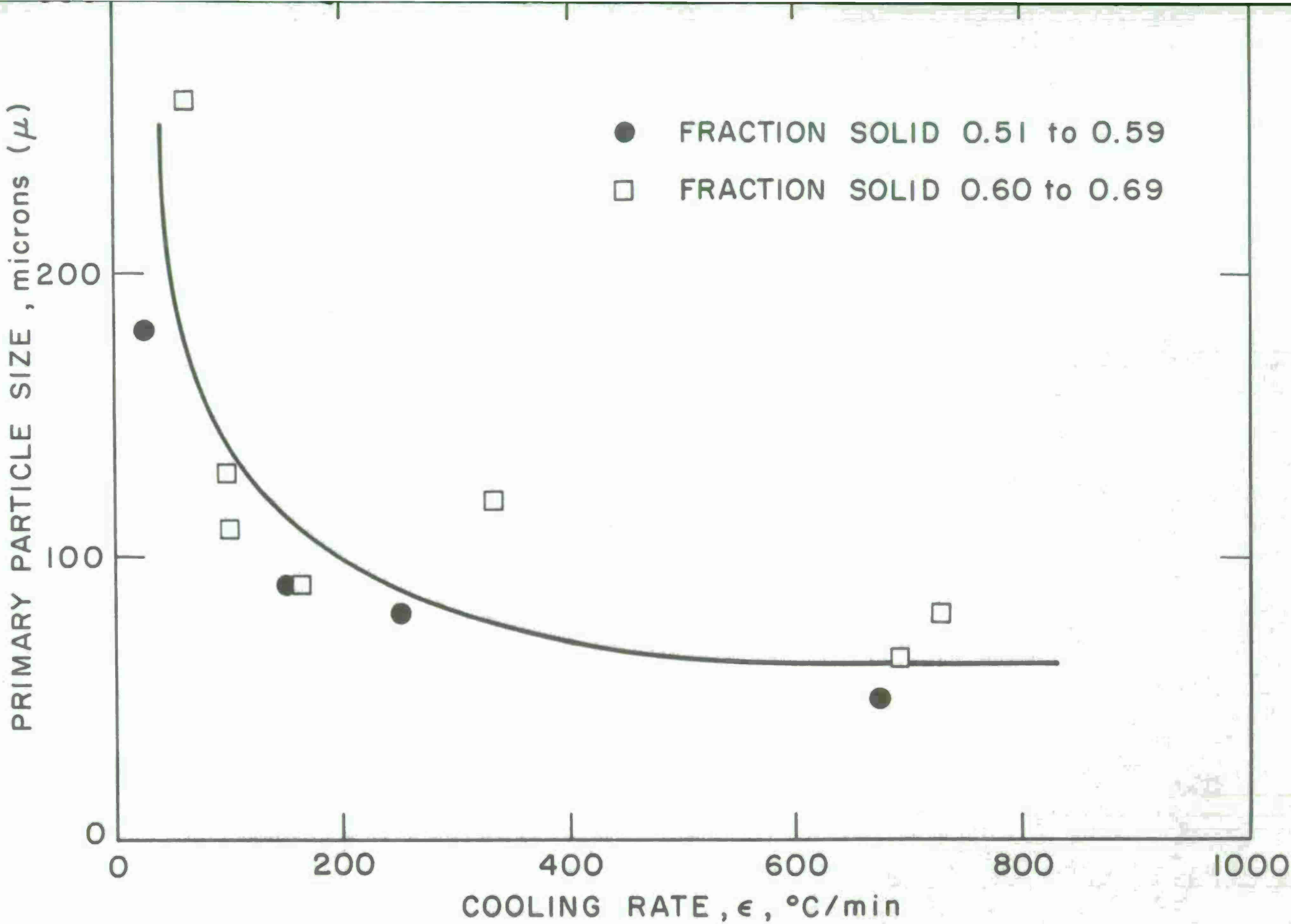


Figure 1. Effect of cooling rate on slurry particle size of Sn-15wt%Pb alloy slurry. Shear rates from 340 sec.$^{-1}$ to 980 sec.$^{-1}$.

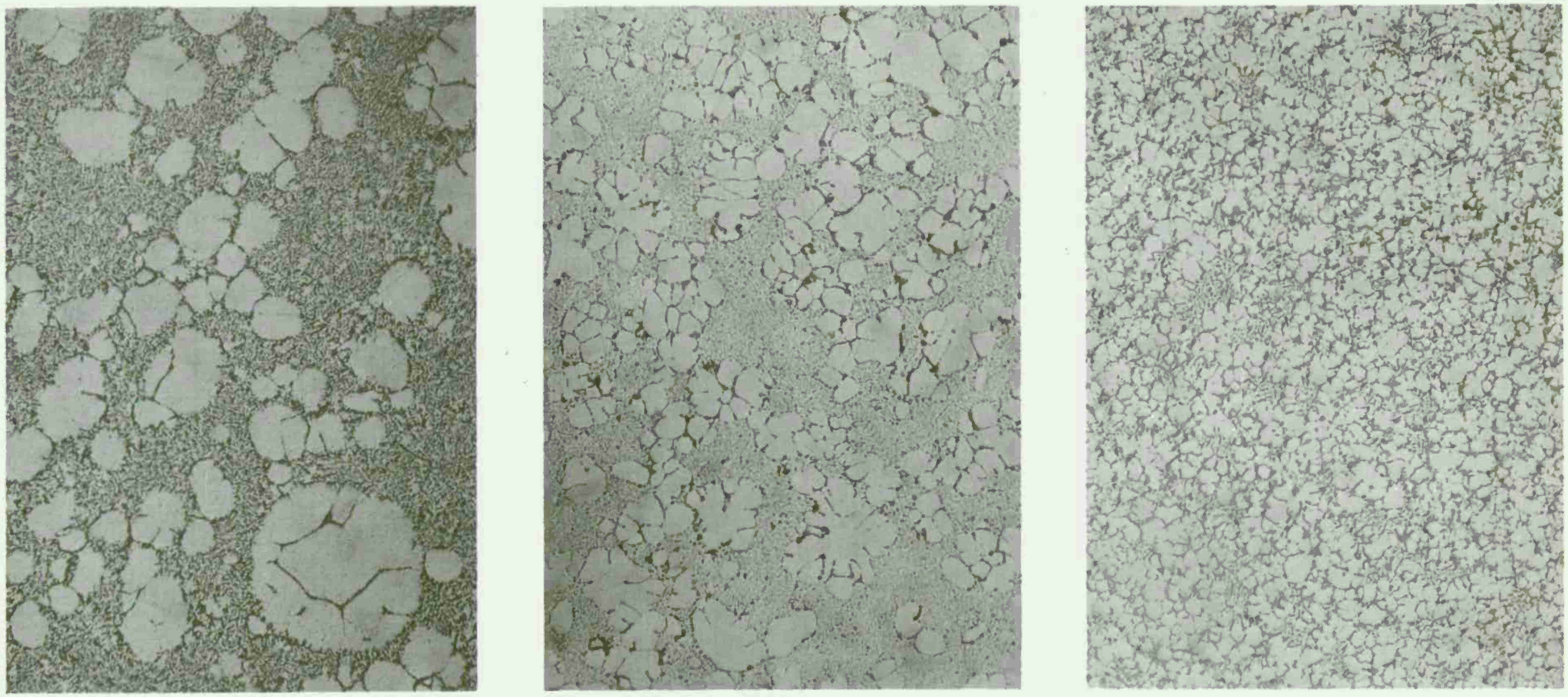


Figure 2. Photomicrographs of Sn-15wt%Pb alloy slurries produced at different cooling rates; (a) ε = 65°C/min., (b) ε = 140°C/min., (c) ε = 675°C/min.; g_s = .5; 100X.

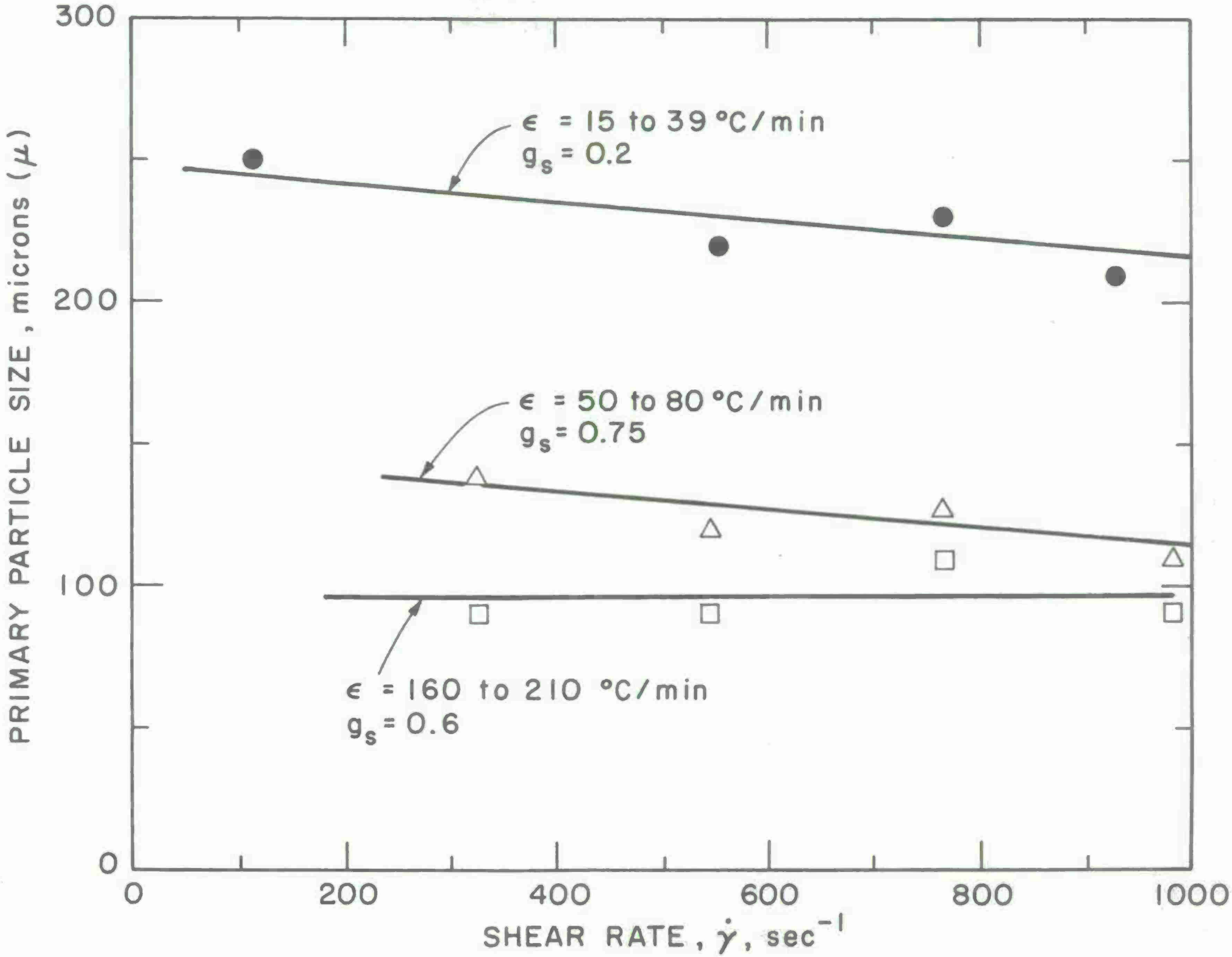


Figure 3. Effect of shear rate on particle size of Sn-15wt%Pb alloy slurries.

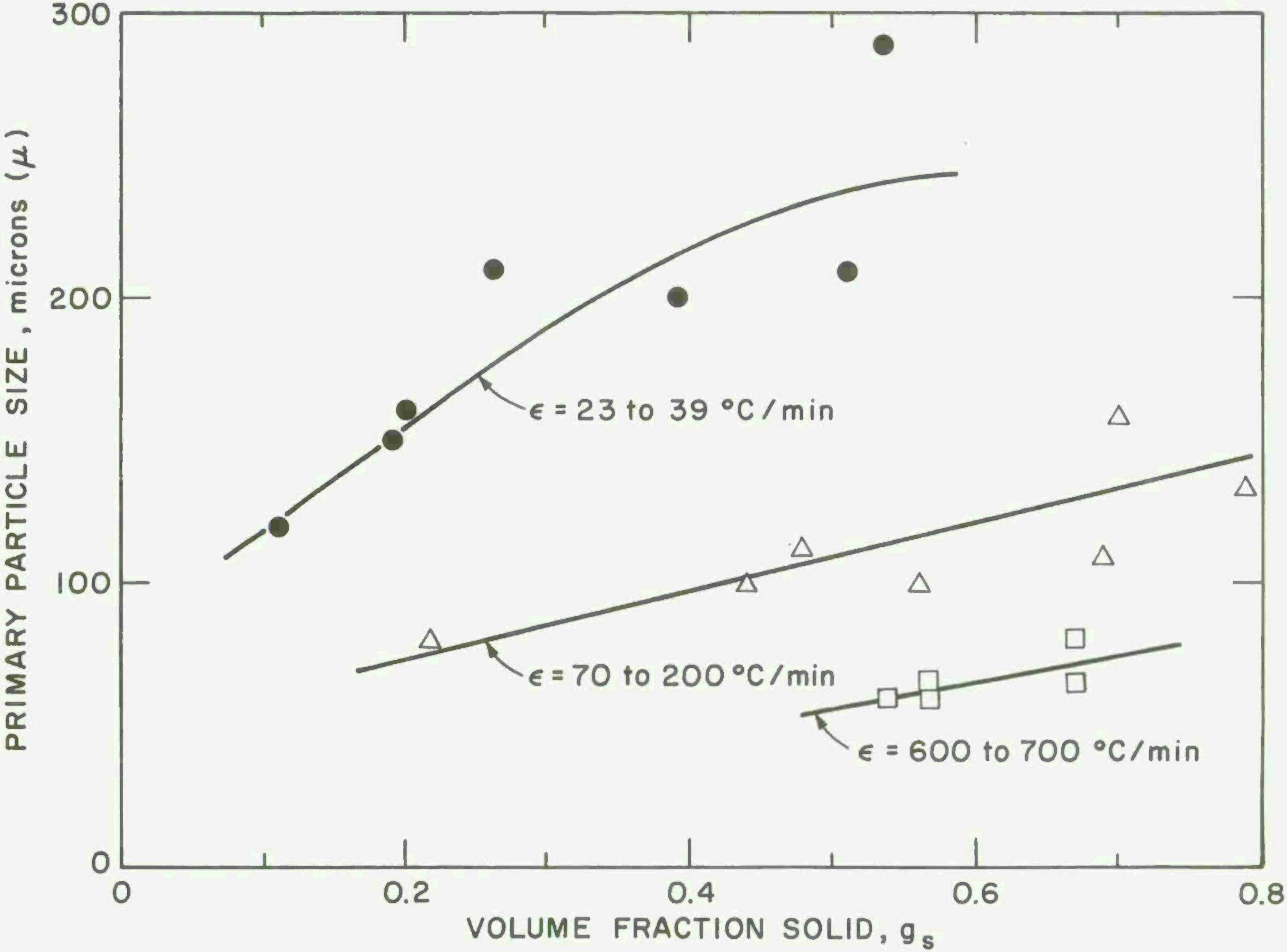


Figure 4. Effect of fraction solid on particle size of Sn-15wt%Pb alloy slurries. Shear rates from 340 $sec.^{-1}$ to 870 $sec.^{-1}$.

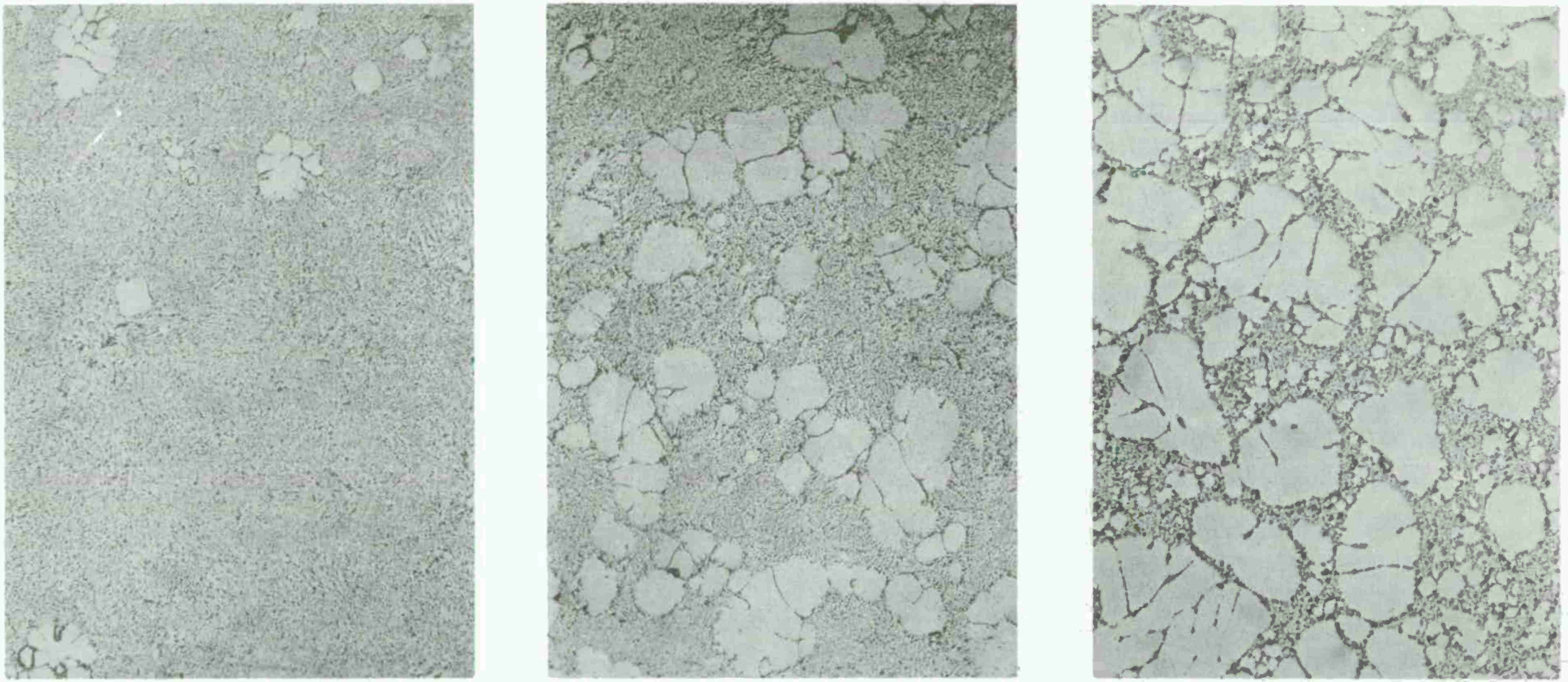


Figure 5. Photomicrographs of Sn-15wt%Pb alloy slurries at various volume fraction solid with slow cooling rates; (a) g_S = .11, ε = 39°C/min., (b) g_S = .39, ε =31°C/min., (c) g_S = .51, ε = 23°C/min.; 100X.

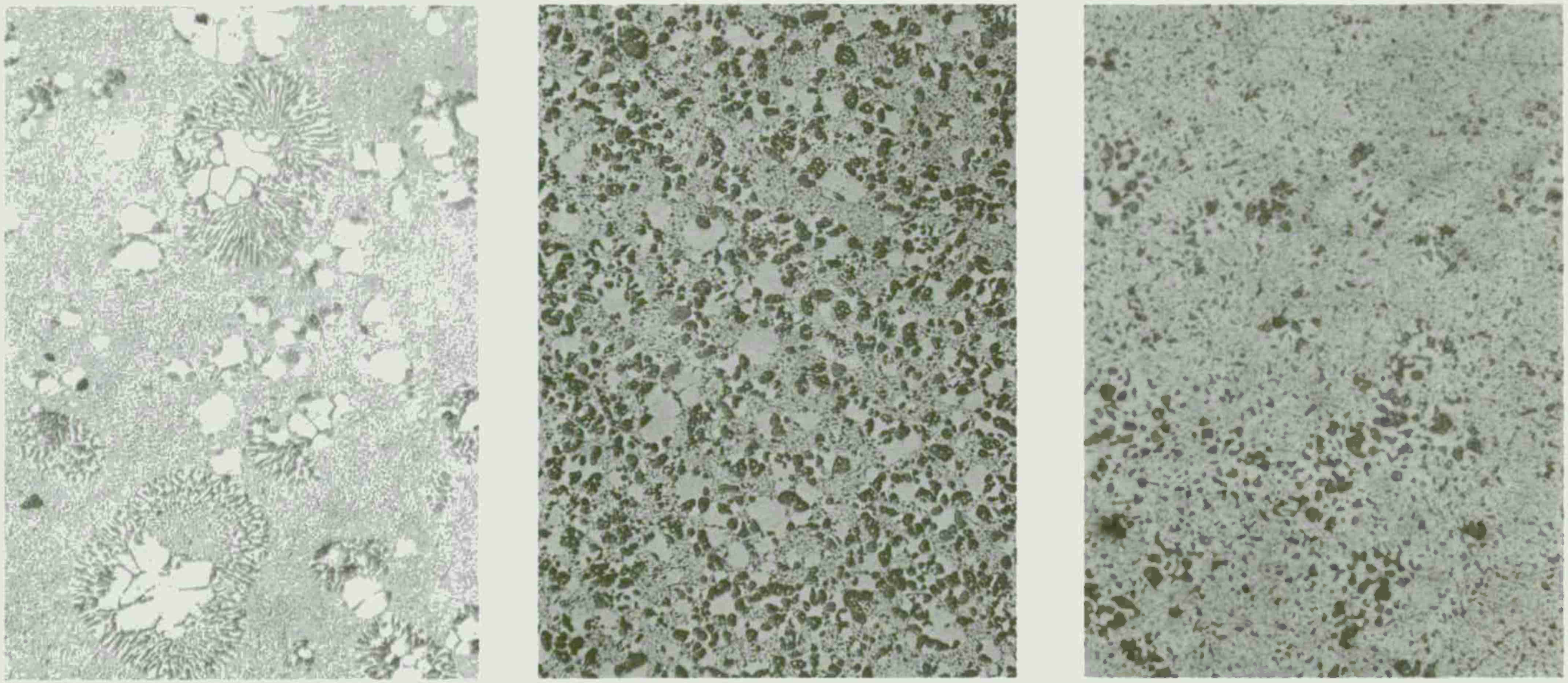


Figure 6. Sn-35wt%Pb alloy slurries with different solidification rates, γ = 540 $sec.^{-1}$; (a) equivalent Sn-15wt%Pb cooling rate ε = 20°C/min., 100X, (b) ε = 100°C/min., 100X, (c) ε = 250°C/min., 200X.

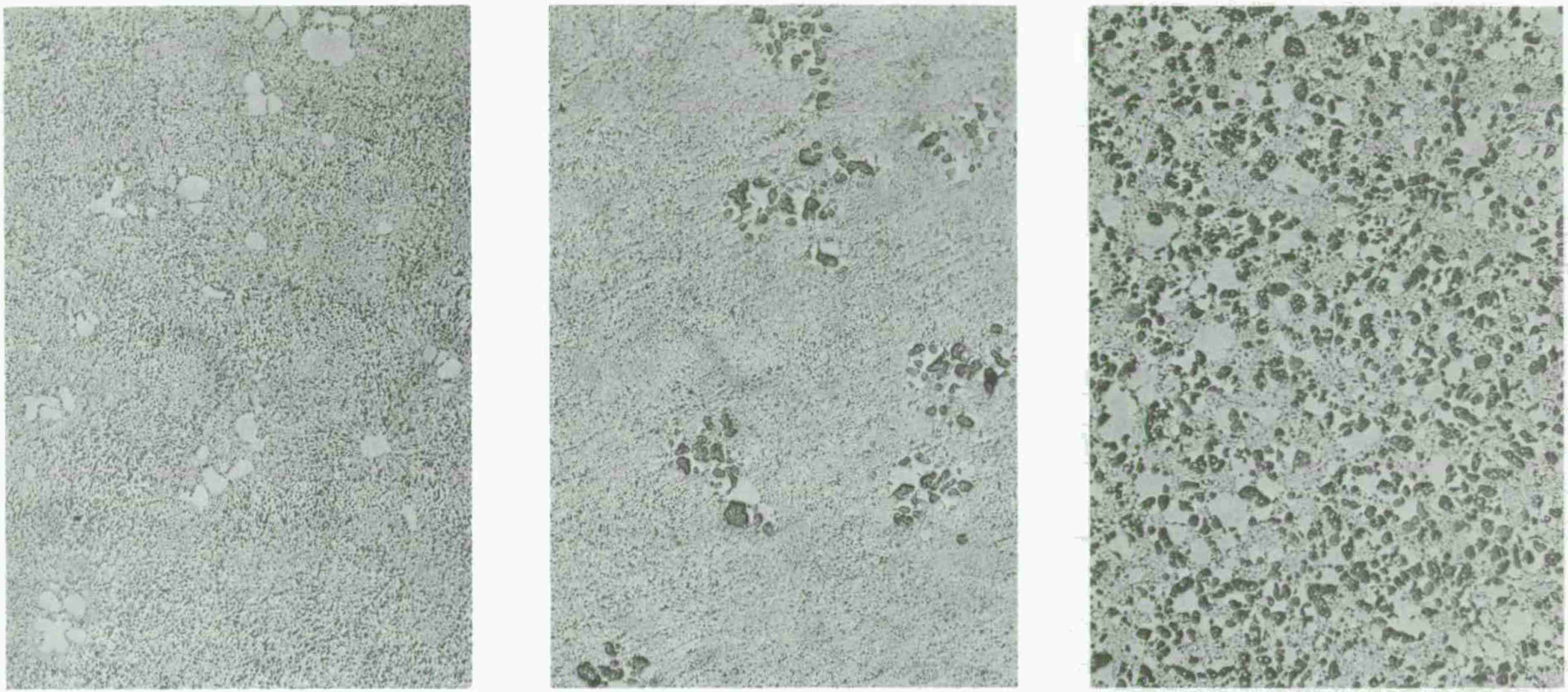


Figure 7. Photomicrographs of Sn-35wt%Pb slurries showing increasing fraction solid; equivalent cooling rate 100°C/min.; (a) g_S = .06, (b) g_S = .15, (c) g_S = .60, 100X.

CHAPTER V. DEVELOPMENT OF NEW CASTING PROCESSES -- "CLAP CASTING"

Summary

The feasibility of a modified Thixocasting process termed "Clap Casting" has been demonstrated using as a model an aluminum-copper alloy. This process eliminates both crucible and alloy injection equipment while automating metal transfer. It is, therefore, particularly attractive for high temperature alloys.

Introduction

The unique properties and die filling characteristics of semi-solid Rheocast and Thixocast metal permit development of a wide range of innovative forming processes. One of these has been carried through an experimental study of its feasibility. In this process the end of a Rheocast rod is heated by induction to a temperature where it is semi-solid. A controllable quantity of metal detaches and gravity delivers the charge material to a pair of horizontally driven dies. This process has the advantages of both eliminating crucibles and automating metal transfer, and as such is attractive for high temperature alloy casting.

Apparatus

A schematic diagram of the apparatus is shown in Figure 1, and a photograph in Figure 2. The apparatus consists of a pair of drive rolls to feed a 1/2 inch diameter rod through a temperature stabilizing water

cooled copper chill into a short 1 inch I.D. induction coil powered by a 20 KW, 400 K cycle Lepel unit. Immediately below this coil, which is insulated from the rod by a transparent Vycor tube, is a photocell detection unit. This unit has two functions. Firstly, it is used to accurately position the rod at the start of each shot, by observation of the degree of shadowing the rod end produces on the photocell. This can be monitored via the output of the detection unit. Secondly, the photocell detector unit is used to trigger, via an appropriate variable delay circuit, Figure 3, the pneumatic cylinder which drives the die cavity plate against the stationary die half. In this operation the Lepel unit is also automatically switched off.

The simple die cavities are made from mild steel and to date have been operated unheated. They are driven by a 3 1/2 inch diameter pneumatic cylinder operating at its maximum pressure of 250 psi to minimize frictional delays.

Procedure

A Rheocast rod 1/2 inch in diameter, cast from a batch Rheocaster was fed by the rolls into the induction coil and its position was adjusted to give a particular output from the photocell detector unit. Power to the coil was switched on at a predetermined level such that a volume of metal of approximately 2 cubic centimeters at the end of the rod partially melted and eventually detached. The falling drop was then sensed by the photocell detector and this triggered, via a preset delay, the pneumatic cylinder.

This drove the dies together to entrap the falling drop which passed adjacent to, but not touching, the vertical center line of the stationary die half. Mechanical ejection of the casting was effected on the die opening sequence via a centrally located pin.

Results and Discussion

After an initial period of operation in which optimum rod position and power levels were established, the apparatus produced consistently approximately 2 cubic centimeters volumes of semi-solid charge material. Sufficient success has been obtained with the apparatus to date to demonstrate the feasibility of such a casting system.

Two types of die cavities have been investigated. These are shown in Figure 4. Castings made with these cavities are shown in Figure 5, and demonstrate that reasonable die fill out has been obtained. A typical microstructure from one such casting is shown in Figure 6. This exhibits the familiar large rounded primary solid and finer dendritic structure formed from the remaining liquid as the casting completes its freezing in the die cavity. While insufficient castings have been made to date to justify radiographic analysis, initial metallographic examination suggests that in castings in which good die fill out is obtained, good internal soundness is also obtained. These features should be further improved by casting slurries of higher fraction solid.

Inconsistencies in the drop detachment position (observed as varying outputs from the photocell detector prior to detachment) have been sufficient

in some cases to cause the dropping semi-solid slug to partially miss the cavity, resulting in non-fill of the die cavity. Some simple changes would eliminate this problem. Firstly, a stepping motor could be introduced into the rod roller drive driven by feedback from the photocell detector unit. This would maintain the rod end position throughout the pre-melting stage. Secondly, a second sensor could be employed which would permit drop velocity to be computed and used to select the delay time in the trigger circuit.

Conclusions

1. A new Thixocasting system termed "Clap Casting" has been investigated which offers the advantage of both eliminating crucibles and alloy injection equipment while automating metal transfer.
2. Preliminary results, using a model aluminum-copper alloy, show that good castings can be produced in this way.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January 1974 - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

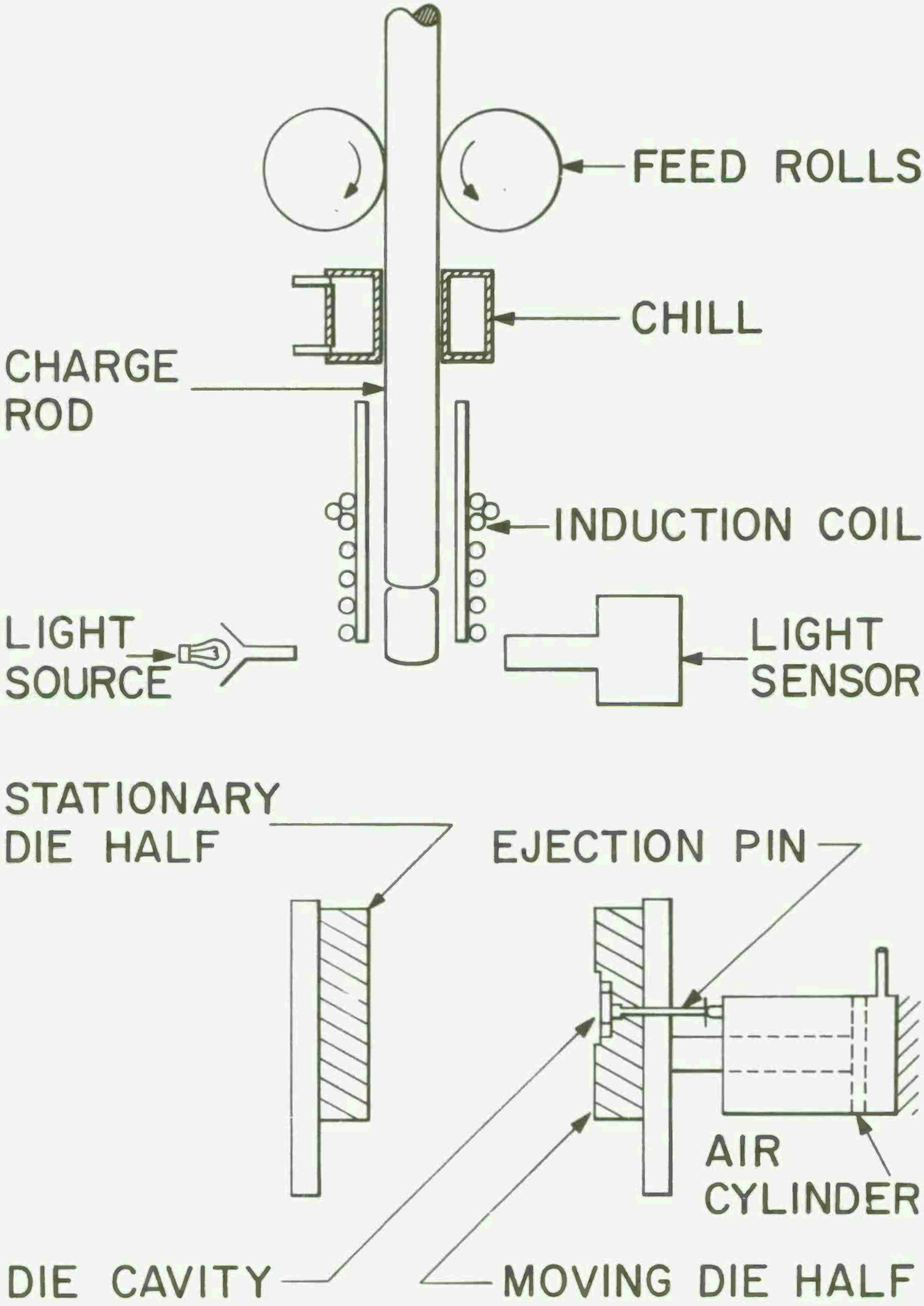


Figure 1. Schematic of the apparatus.

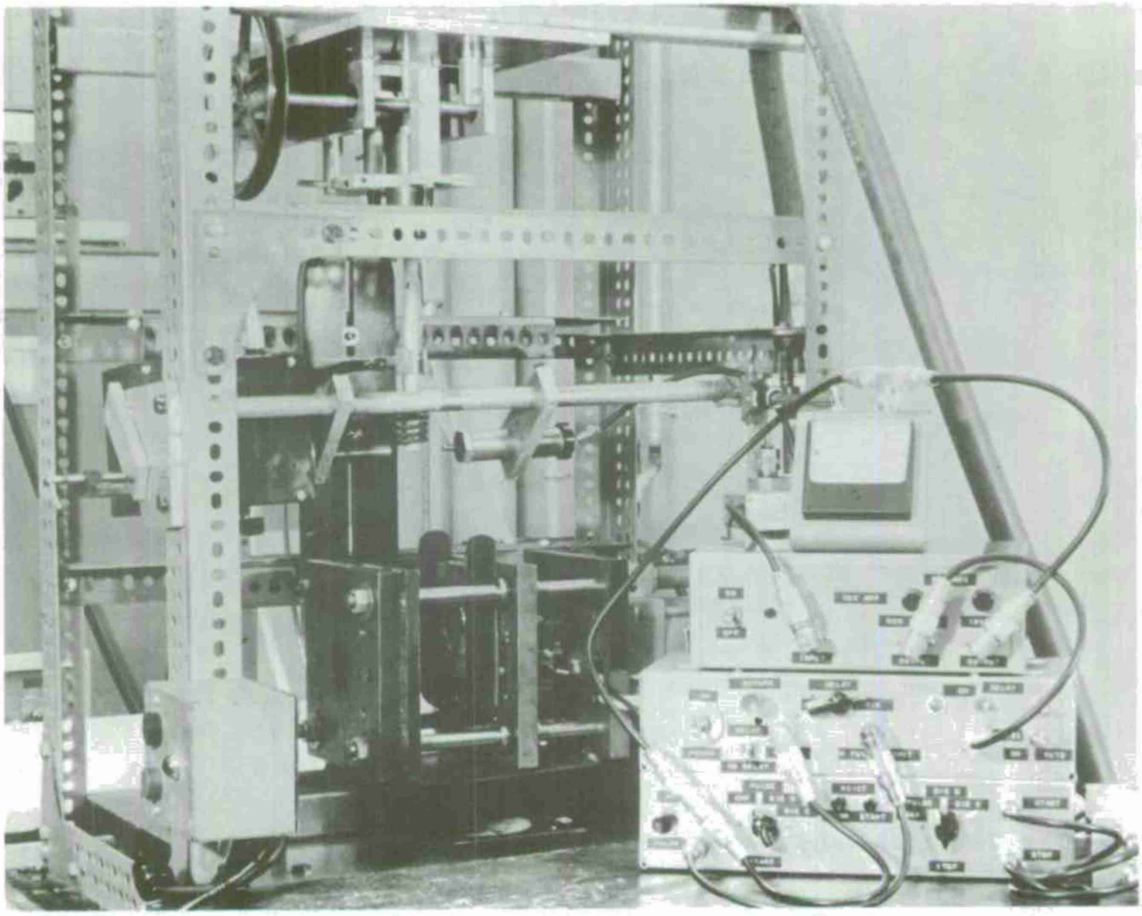


Figure 2. Photograph of the laboratory set up.

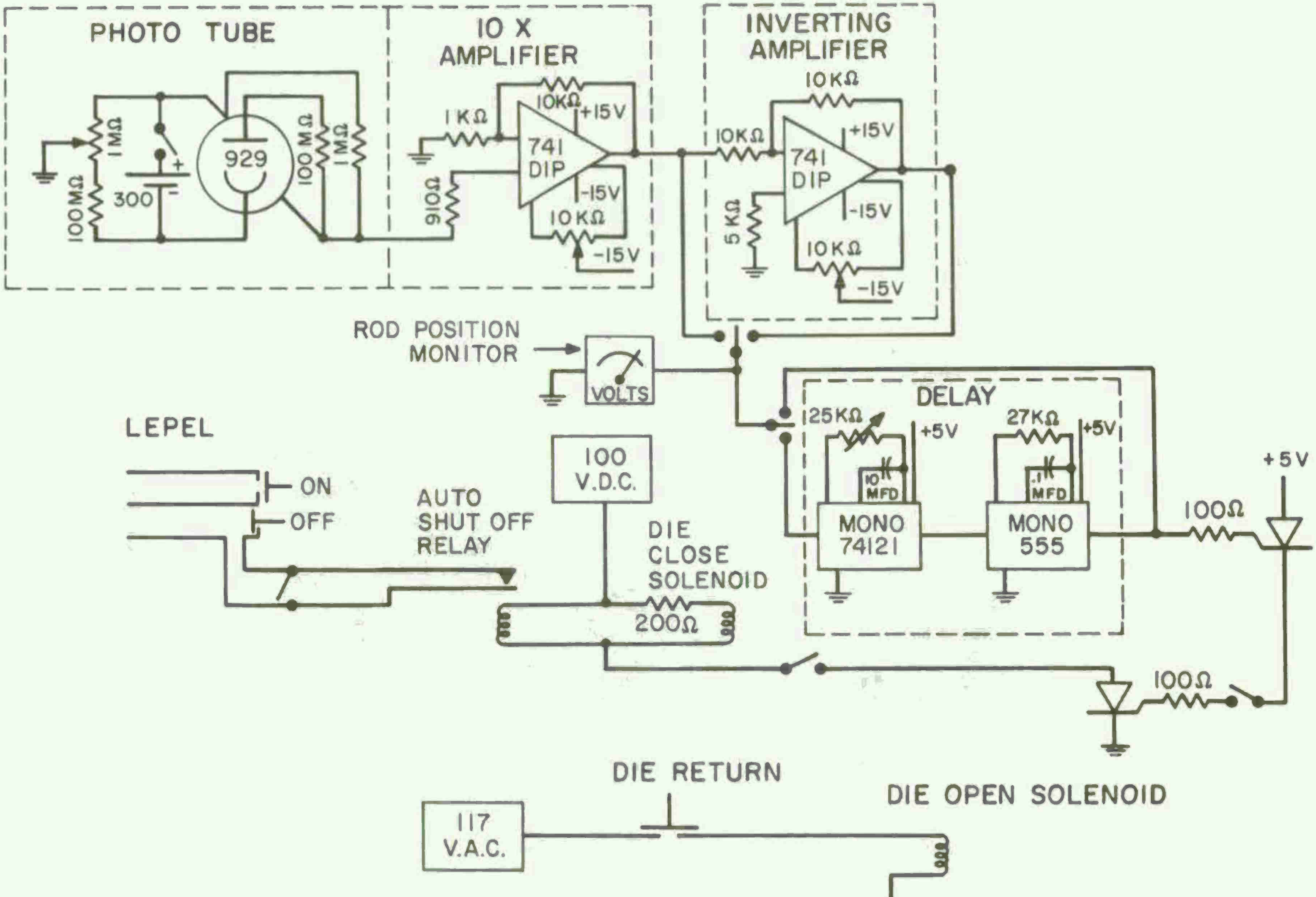


Figure 3. Rod position monitor and casting control circuit.

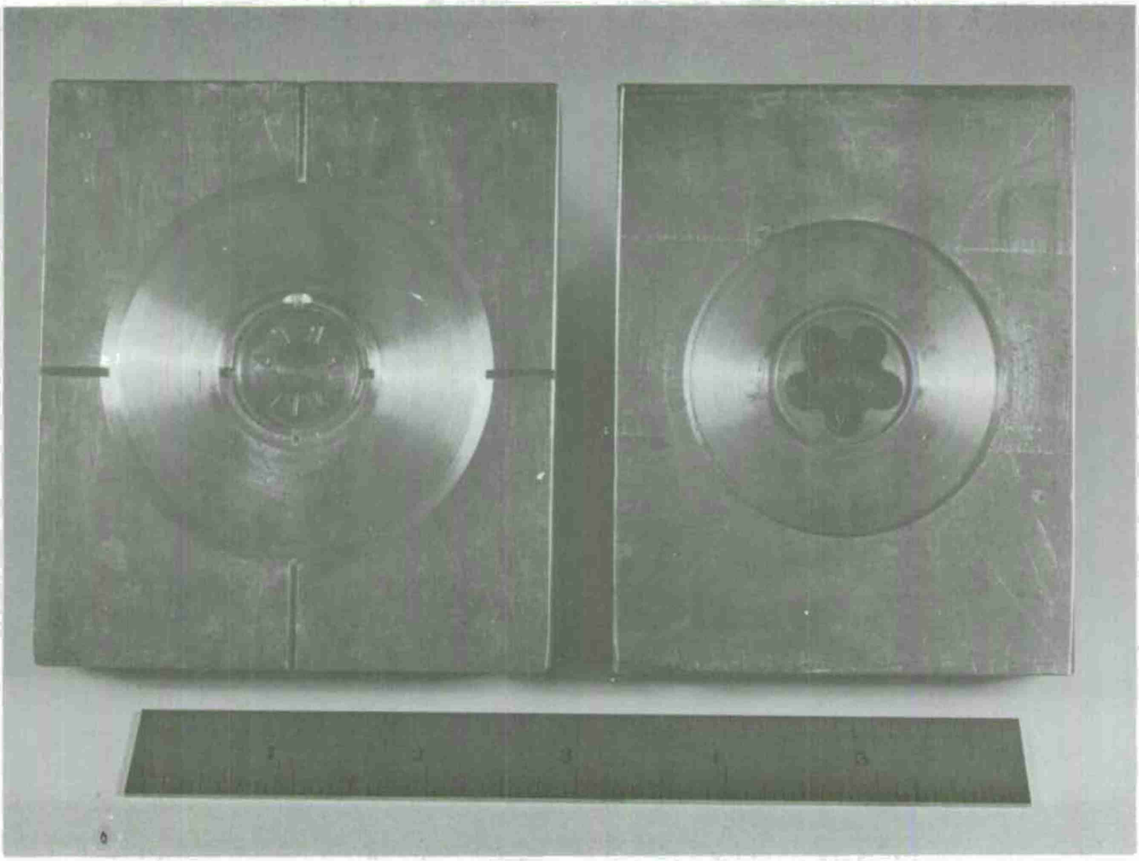


Figure 4. Photographs of the experimental die cavities.

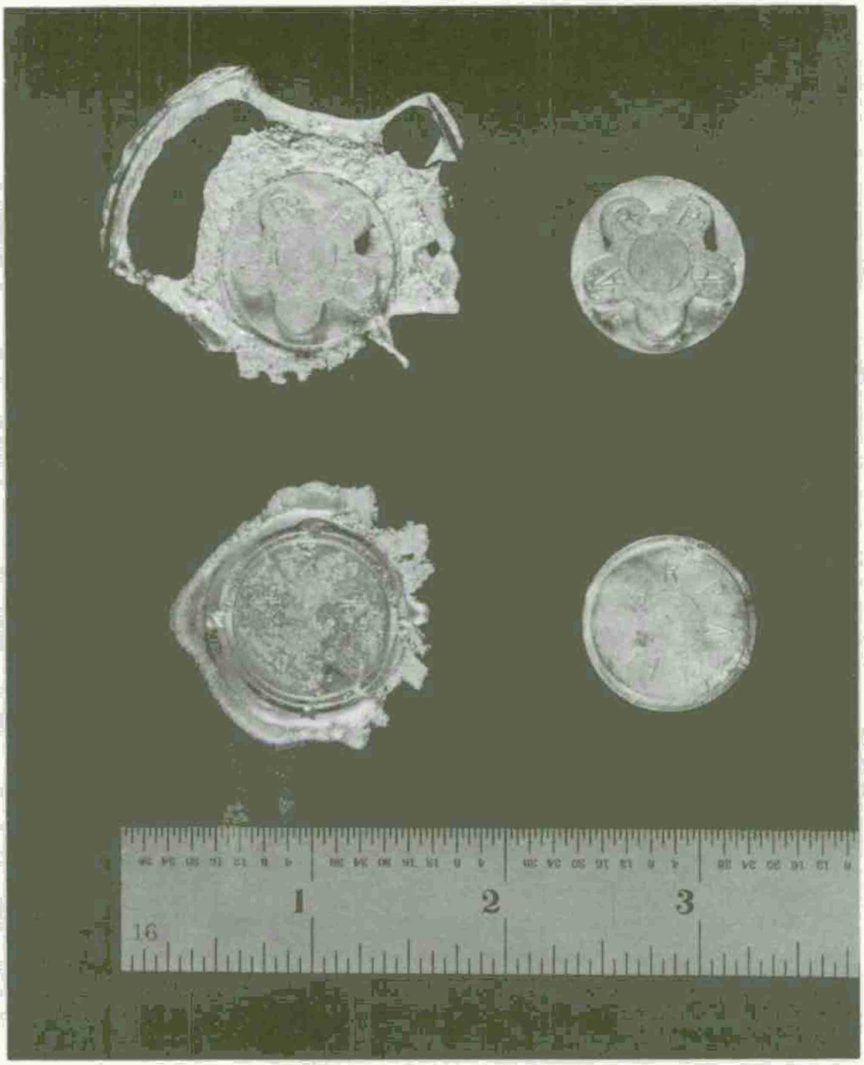
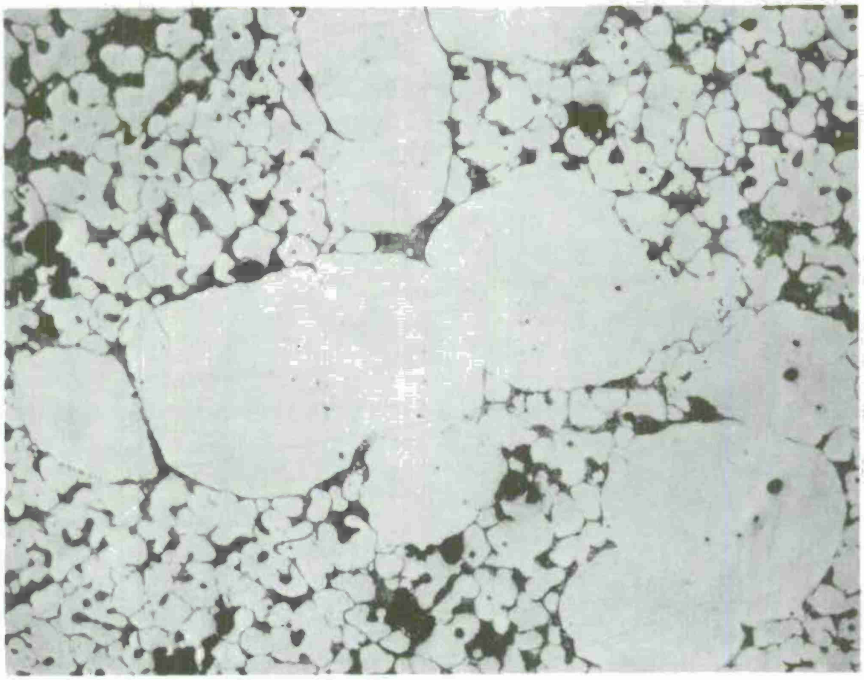


Figure 5. Photographs of castings made.



50X

Figure 6. Micrograph of aluminum-copper Thixocastings.

CHAPTER VI. ELECTROMAGNETIC INJECTION OF SEMI-SOLID ALLOY

Summary

Two different types of electromagnetic injectors have been studied and comparisons between them made on the basis of experiments and theory. The first type of device is the "induction" machine, reported earlier. The second is the "universal" machine described below. Theory and experiment agree well in both machines leading us to believe that we understand the processes involved. A simply and inexpensively constructed apparatus can propel metal at velocities of 20 m/sec. or more corresponding to casting pressures of 400 psi.

Introduction

The purpose of this work is to replace the piston - shot sleeve part of a die casting machine in injecting metal into a die.

Work during this contract year has centered upon the evaluation of two machines, which we term the induction and universal types. The first considered was the induction machine, shown schematically in Figure 1. This machine relies upon the principle that a current varying in time above a conducting body will produce field and induce current in the conductor in such a way that there is repulsion between the two. In order to determine the characteristics of this device and its applicability to casting different metals, the following program was followed:

(1) A machine was constructed which was capable of making simple castings. This has been described in a previous report.[1]

(2) A theory for determining the net force upon the slug was developed and tested experimentally. This model made use of experimentally determined circuit parameters. It includes scaling of the force with size and conductivity. This theory was tested experimentally, as described below.

(3) A theory describing the fluid mechanics of a jet impulsively injected into a simple cavity was developed. This theory seems to explain qualitatively results obtained in casting experiments.

(4) On the basis of (1), (2) and (3) above, the practical limitations of the device were considered, along with consideration of the capital costs of such a machine.

These topics will be discussed in the following section.

A second type of machine, the "universal" type, was considered next as a possible answer to some of the problems encountered in the investigation of the induction machine. The universal machine is shown in Figure 2. As of the end of this report period, the following work has been completed:

(1) The construction of a simple pendulum experiment to test the idea of the universal machine.

(2) The development of a theory to describe the pendulum experiment and a general theory to describe the driver section actually envisioned.

(3) Experiments in ejecting rheocast lead-tin alloy from a prototype driver section.

These three topics will be discussed in the section titled, "The Universal Machine".

The Induction Machine

Results of casting experiments have been described previously,[1] so we will begin here immediately with our efforts to understand the physical basis for those results.

The first part of this task is to find the net electromagnetic force on the fluid. We will cast our model in lumped parameter terms, this being most directly connected to experimental measurements. The circuit model for this machine is shown in Figure 3. Then we have:

$$i_p = \mathrm{Re}[\,\hat{i}pe^{st}],\quad s \simeq \frac{R}{2L} + \sqrt{(\frac{R}{2L})^2} - \frac{1}{Lc} \tag{1}$$

$$i_s = \mathrm{Re}[\,\frac{sM\hat{i}_p}{sL_s + R_s}\,e^{st}] \tag{2}$$

L_p and i_s are the primary and secondary currents, and s is the natural frequency of the circuit.

For consideration of the net force, we need only consider the magnetic field caused by the driving coil:

$$B = \frac{\mu_o f(r_o, z)}{r_o} \, ip \tag{3}$$

f_o is a dimensionless function of r_o and z, and μ, is the permeability of free space ($4\pi \times 10^{-7}$ H/m).

$$F = \frac{\mu_o f(r_o, z)}{r_o} \, \mathrm{Re}\,[\,\hat{i}_p e^{st}]\ \mathrm{Re}\,[\,\frac{sM\hat{i}_p}{sL_s + R_s} e^{st}]\ .\ 2\pi r_o \tag{4}$$

$$= \frac{\mu_o f(r_o, z)}{r_o} (2\pi r_o)\ \mathrm{Re}\,[\,\frac{sM\hat{i}_p}{sL_s + R_s} e^{2st} + \frac{sM\hat{i}_p\hat{i}^*_p}{sL_s + R_s} e^{2s_r t}] \tag{5}$$

$$m\,v = \frac{\mu_o f(r_o, z)}{2r_o} (2\pi r_o)\ \mathrm{Re}\,[\frac{M\hat{i}_p}{2(sL_s + R_s} + \frac{sM\hat{i}_p\hat{i}^*_p}{2s_r(sL_s + R_s)}] \tag{6}$$

F is the instantaneous force; v is the final velocity. Simplifying and substituting for i_p, we have:

$$m\,v = \frac{\pi(CV_o)^2 |s|^4 (\frac{L_s}{R_s})^2 K^2 L_p \mu_o f(r_o, z)}{2s_r} \tag{7}$$

$$K = \frac{M^2}{L_s L_p} \tag{8}$$

This holds assuming $\frac{vL_s}{R_s} \ll 1$ and $(\frac{S_r}{S_i}) \ll 1$. A more complicated general relation follows straightforwardly from the next to last equation. For typical experimental values this approximate expression is accurate to within 20 percent.

The net specific impulse predicted by this theory was substantially that found experimentally, as shown in Figure 5. The experiment was done with the same equipment as described in a previous report.[1] The values for the circuit parameters were determined directly by small signal analysis using an oscillator and diagnostic equipment.

From equation 7, we can see that the impulse delivered is to R_s^{-1}, the geometry and primary circuit characteristics being held constant. R_s is proportional to σ^{-1}, σ being the conductivity of the fluid. So the force to be expected goes as σ^2. (This is true, of course, only for small values of σ, such as we will here encounter.) The implication of this is that in going from a solid alloy slug to a semi-molten steel slug of the same size we will have only 4 percent as much velocity. (Material properties for Cerelow alloy and other metals are listed in Table 1.) As we increase the size of the slug system, we receive a greater impulse, but this is counteracted by the increase in mass of the system. For steel, then, we can conclude that to obtain velocities suitable for casting requires either a capacitor bank with a much quicker discharge time or a much bigger system, since the scaling laws favor size. Since neither of these courses seems practical at this time, we were led to look for another type of device.

The Universal Machine

Since the problems with the induction machine is too little induced current in the fluid, an alternative that suggests itself is to impose a current through the fluid. The disadvantage of this method is that it requires contact between an electrode and the fluid. The advantage is that it is very insensitive to fluid conductivity. There are ways in which to meet the first objection, one of which is shown in Figure 6. In this system the electrodes would be cast and would be fed in and melted by an induction heating coil. When enough Rheocast material had accumulated, the heating coil would be removed and the material driven into the mold below. A simple thermal analysis indicates that this could well be feasible, though an induction power supply of ~30 KW would be required. Another alternative is to simply clamp water cooled electrodes on to the metal just before discharge and allow for a reasonable amount of erosion by pushing the electrodes in slightly periodically. This also seems possible from a thermal standpoint. The first experiment done is shown in Figure 7. It was chosen because of the very simple fluid mechanics that results. This simple fluid pendulum experiment was done to test the imparting of momentum to a fluid in an unambiguous way. The theory of this device is composed of two parts: the amount of momentum imparted by the electric pulse and the response of the pendulum (maximum height attained) for a given momentum. We will consider the first part as a special case of the general driver theory given below. The maximum height, x_0, is given by

$$x_o = \frac{\ell}{2g} v_o \tag{9}$$

This results from direct application of Bernoulli's equation.

The Universal Machine. The coordinates and variables used in the following derivation are shown in Figure 8. The fluid velocity at the bottom of the injector section is derived under the following assumptions, which are justified below:

(1) The velocity of the middle stream of the exiting jet is governed by the equations of inviscid fluid mechanics.

(2) The electrical force acts as a mechanical impulse.

(3) The magnetic field is imposed by the coil; image currents make no contribution to the field.

(4) The field is uniform over the region of interest.

Justification of Assumptions.

(1) The time associated with the diffusion of the viscous boundary layer into the bulk of the flow is

$$\tau_\nu = \frac{w^2 \rho}{\eta} \tag{10}$$

The transport time is

$$\tau_t = \frac{\ell}{v} \tag{11}$$

We are concerned with velocities of 10m/sec. and depth of 1 cm. The density and viscosity in MKS units are about 7×10^3 and .5 respectively. Thus:

$$\tau_\nu \sim \frac{(10^{-2})^2 \; (7 \times 10^3)}{(5 \times 10^{-1})} \sim 1 \text{ sec.} \tag{12}$$

So the material is through the system before the effects of viscosity can reach the free stream.

(2) The electrical pulse is approximately 1 m/sec. long. Thus it acts as an impulse for velocities less than ~20m/sec. For some of the higher velocities attained experimentally, this assumption begins to fail.

(3) The critical parameter here is $\omega\tau_m$, ω being the frequency of excitation and τ being the magnetic diffusion time $\mu\sigma l^2$. Typically $\mu \sim 10^{-6}$ and $\sigma \simeq 10^6$, so that $\tau_m \sim 10^{-6}$ sec. The frequencies used are all less tha k kHz, so that $\omega\tau_m \leq 10^{-3}$ This means that the ratio of induced to applied field is roughly one part in 10^3.

(4) This can only be related to a particular coil. In the case of the coil used experimentally, the field varied by no more than 40 percent over the face of the slug.

<u>Derivation of Velocity</u>. The velocities and forces for an inviscid system are related by Bernoulli's equation:

$$\rho \int_a^b \frac{\partial \bar{v}}{\partial t} \cdot d\ell + P_b + \rho \frac{v_b^2}{2} = P_b + \rho \frac{v_a^2}{2} \quad \int_a^b \bar{f} \cdot d\bar{\ell} \tag{13}$$

Or, in moving coordinates

$$\rho \frac{d}{dt} \int_a^b \bar{v} \cdot d\ell + P_b - P_a - \rho (v_b^2 - v_a^2) = \int_a^b \bar{f} \cdot d\bar{\ell} \tag{14}$$

If $\bar{B}$ is uniform, then:

$$\bar{F} = \bar{J} \times \bar{B}, \ \bar{B} \text{ a constant}$$

$\bar{J}$ is only in the x and y directions; $\bar{B}$ is uniform and in the z direction.

$$F = (\bar{J}_x \hat{i}_x + J_b \hat{i}_y) \times (B_o \hat{i}_z) \tag{15}$$

$$= -J_x B_o \hat{i}_b + J_b B_o \hat{i}_x$$

$$\nabla \times \bar{F} = \frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y} \ \hat{i}_z \tag{16}$$

$$= B_o \ \frac{\partial J_y}{\partial y} + \frac{\partial J_x}{\partial x}$$

$$\text{but } \bar{\nabla} \cdot \bar{J} = 0, \text{ so}$$

$$\bar{\nabla} \times \bar{F} = 0$$

$$\bar{F} = \bar{\nabla} \times \bar{c}$$

where $\bar{c}(\bar{r}) = B_o \int_{\bar{r}_o}^{\bar{r}} \bar{J}(\bar{r}) \times d\bar{\ell}$

If we consider the velocity component v_x in Bernoulli's equation, we obtain the result:

$$\rho \frac{d}{dt} \int_b^a v_x dx + P_b - P_a - \rho (v_b - v_a) = iB_o \tag{17}$$

This is independent of the particular distribution and direction of the current.

Since the electrical force is taken as an impulse, only the following terms remain:

$$\rho \frac{d}{dt} \int_a^b v_x dx = iB_o \tag{18}$$

or

$$\rho\ell \frac{du}{dt} \int_a^b \frac{v_x}{u} d\left(\frac{x}{\ell}\right) = iB_o \tag{19}$$

Evaluating the above integral requires a detailed knowledge of the velocity distribution. We do not know this, but can guess that in normalized form it should be of order unity. For a capacitor discharge the above equation quickly becomes

$$v = \frac{\frac{1}{2} cV^2 \alpha}{\rho \ell w R_p \int_a^b \frac{v_x}{v} d(\frac{x}{\ell})} \tag{20}$$

Where R_p is the circuit resistance and α is the ratio of B_o to i.

Experiment

The pendulum experiment described above was constructed with the following parameters measured:

$$C = 3.6 \times 10^{-3} \text{ F}$$
$$\alpha = 2.0 \times 10^{-4}$$
$$\rho = 7.2 \times 10^{3} \text{ kg/m}^3$$
$$\ell = .45 \text{ m}$$
$$w = 2.0 \times 10^{-2} \text{ m}$$
$$R_p = .07\Omega$$

The experimental results of the pendulum experiment are shown in Figure 9. This agreement leads us to believe that the momentum impulse theory adequately describes this interaction.

A driver section such as described above was constructed for tin-lead alloy. Rheocast slugs were partially melted into the liquid-solid range in the shot chamber and ejected past a photo-electronic timing apparatus via a capacitor discharge.

For our experiment:

$$C = 4.75 \times 10^{-3} \text{ F}$$
$$\alpha = 2.0 \times 10^{-4}$$

$$\rho = 7.2 \times 10^3 \text{ kg/m}^3$$

$$\ell = 10^{-1}\text{m}$$

$$w = 10^{-2}\text{m}$$

$$R_p = .05\Omega$$

A Thixocast slug is melted to the appropriate fraction solid. At that point one of the side walls is removed and the driver coil put into place and secured. The pulse is then applied to the coil and to the electrodes.

Velocity of the ejected fluid was measured via two photocells and timing circuitry. The arrangement of photocells and amplifiers is such that they respond to the first inpingement of the metal into the light beams with a delay of less than .2 m/sec. The resulting measured velocities are shown in Figure 10. The theoretical line shown uses a value for the fluid mechanical constant α of .8.

The correlation between theory and experiment evidenced here leads us to believe that:

(a) The theory developed is a true picture of the way in which the device works and can be used as a reliable guide for further designs.

(b) That such an apparatus can propel masses of metal on the order of a pound at velocities of 20 m/sec., ρv^2 (the dynamic pressure) at this velocity is 400 psi.

Conclusions

1. Theory and experiment agree well in both machines leading us to believe that we understand the processes involved.
2. A simply and inexpensively constructured apparatus can propel metal at velocities of 20 m/sec. or more corresponding to casting pressures of 400 psi.

References

1. M. C. Flemings et al., "Machine Casting of Ferrous Alloys", Interim Technical Report, ARPA Contract DAAG46-C-0110, 1 January - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

TABLE I

Material	Approximate Conductivity (mho/m)	Density (kg/m)
Cerelow-117	2×10^6	6.8×10^3
Aluminum (Solid, 25°C)	3.5×10^7	2.7×10^3
Aluminum (Liquid, 700°C)	6×10^6	2.7×10^3
Steel (Liquid)	5×10^5	7×10^3

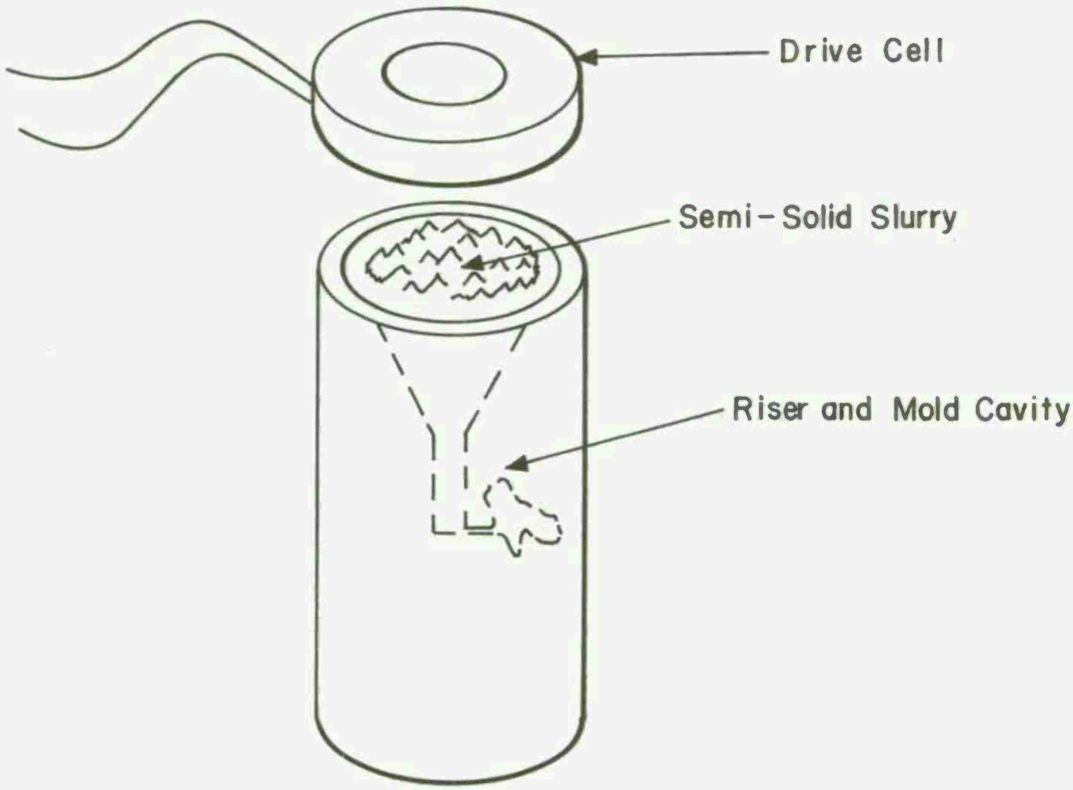


Figure 1. The Injection Machine

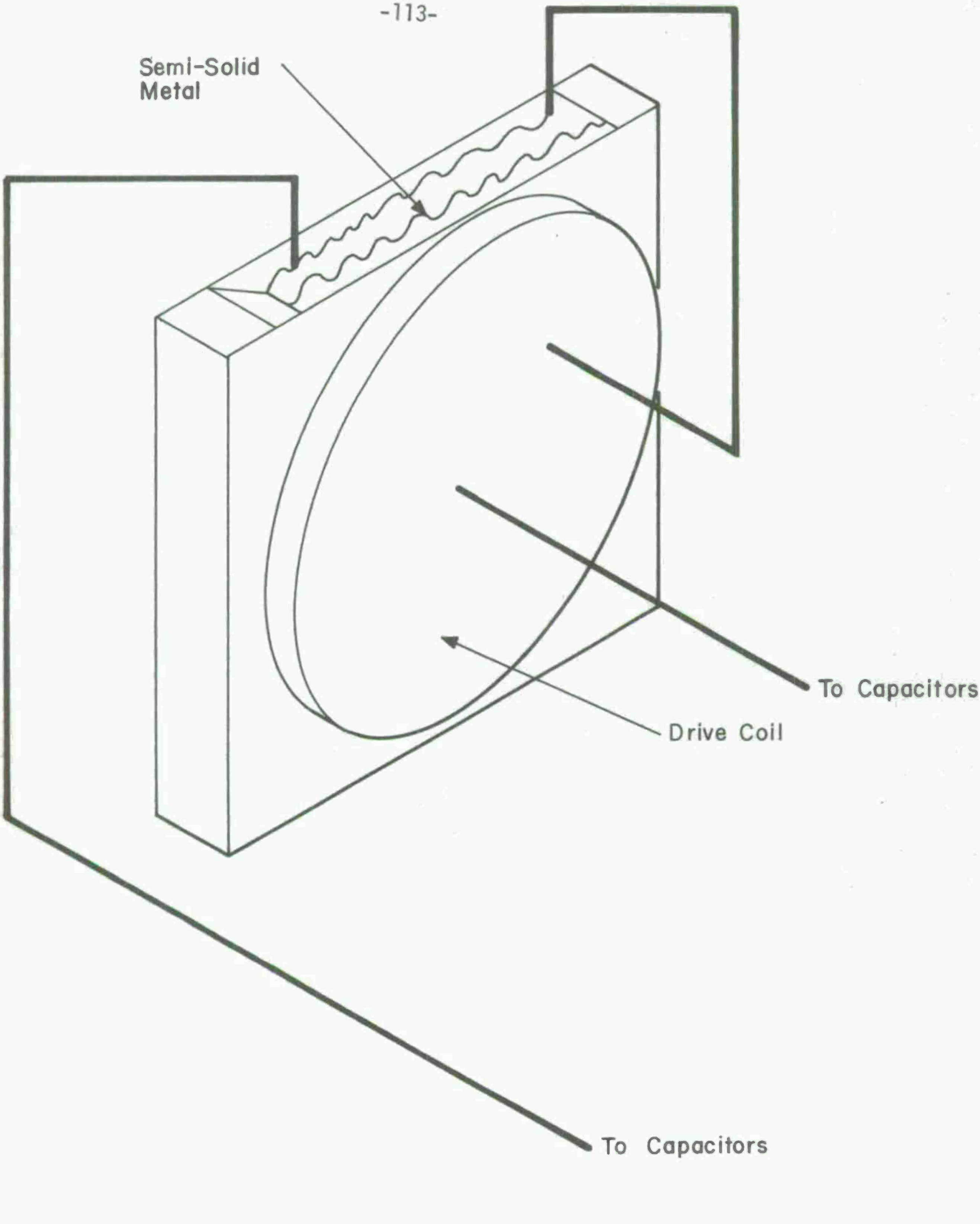


Figure 2. The Universal Machine

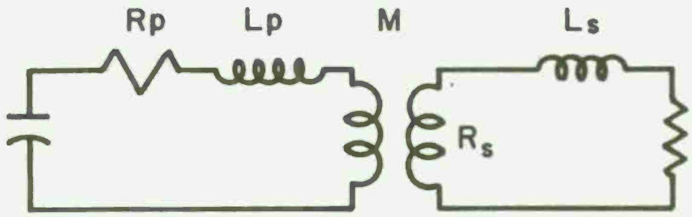


Figure 3. Equivalent Circuit for Induction Machine

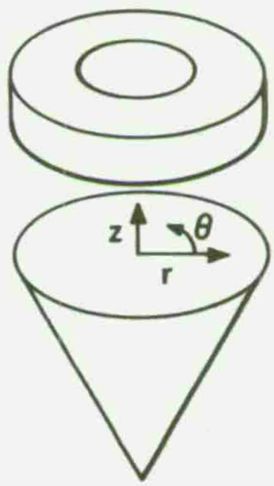


Figure 4. Coordinate System in Induction Machine

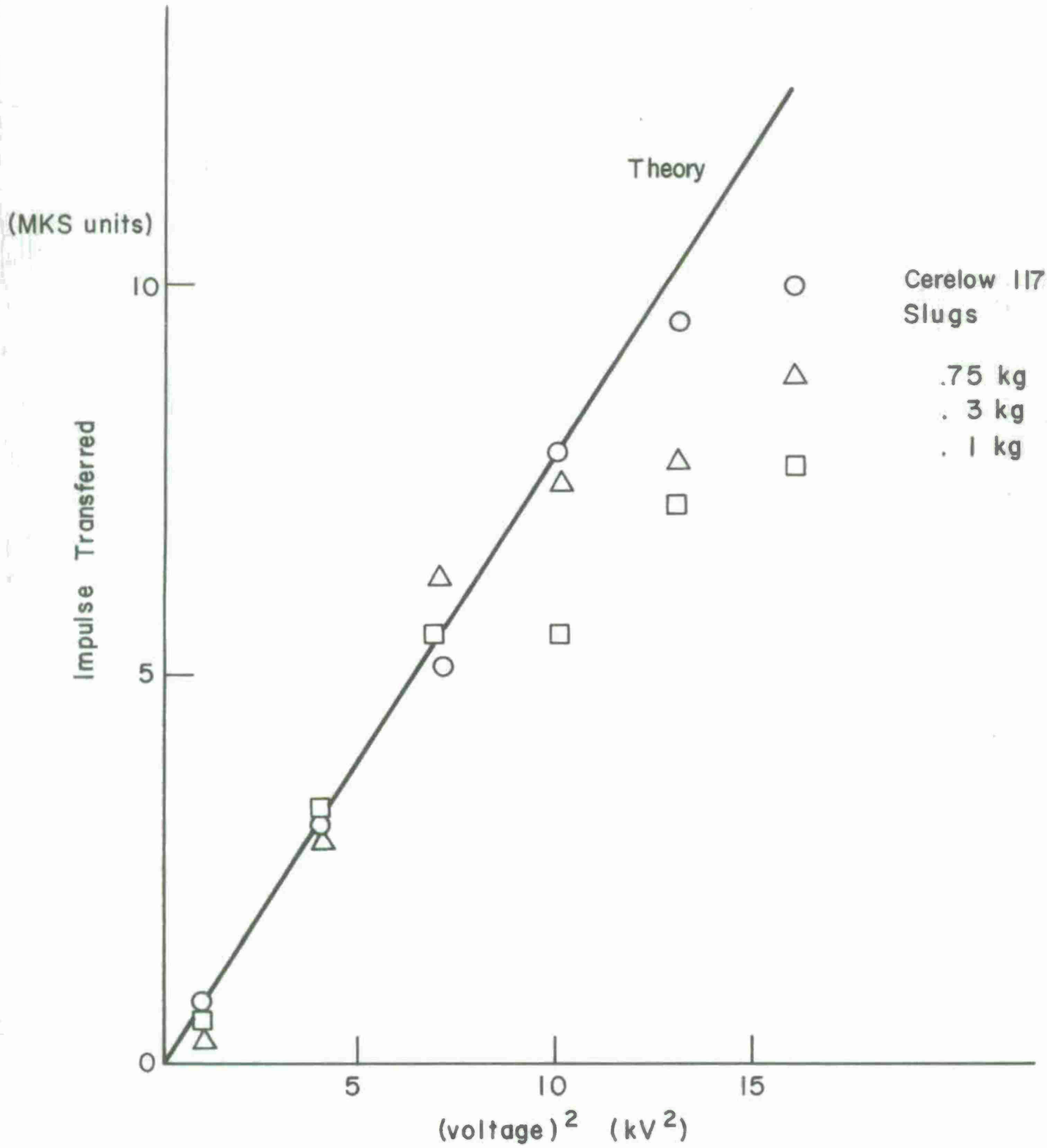


Figure 5. Total Transferred Impulse in Induction Experiment

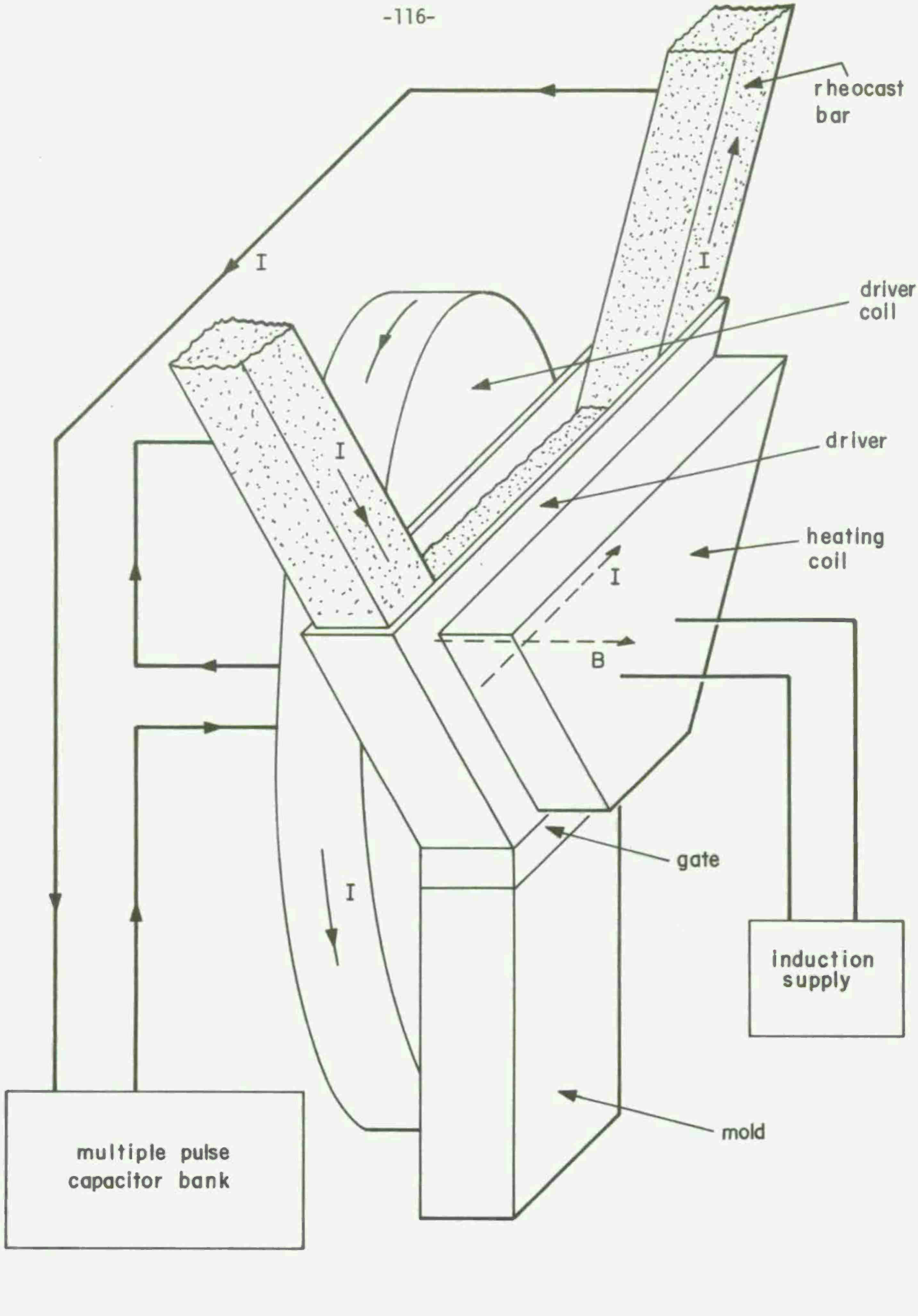


Figure 6. Schematic of Electromagnetic Injection Apparatus

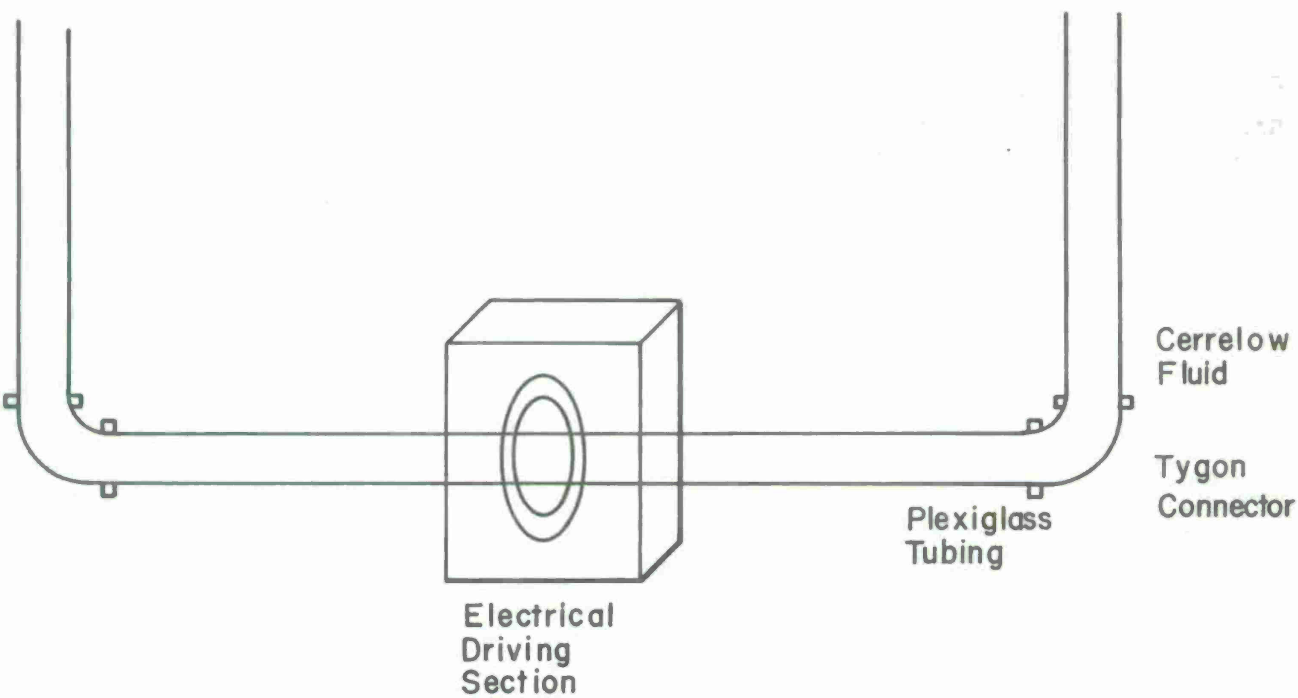


Figure 7. Universal Pendulum Experiment

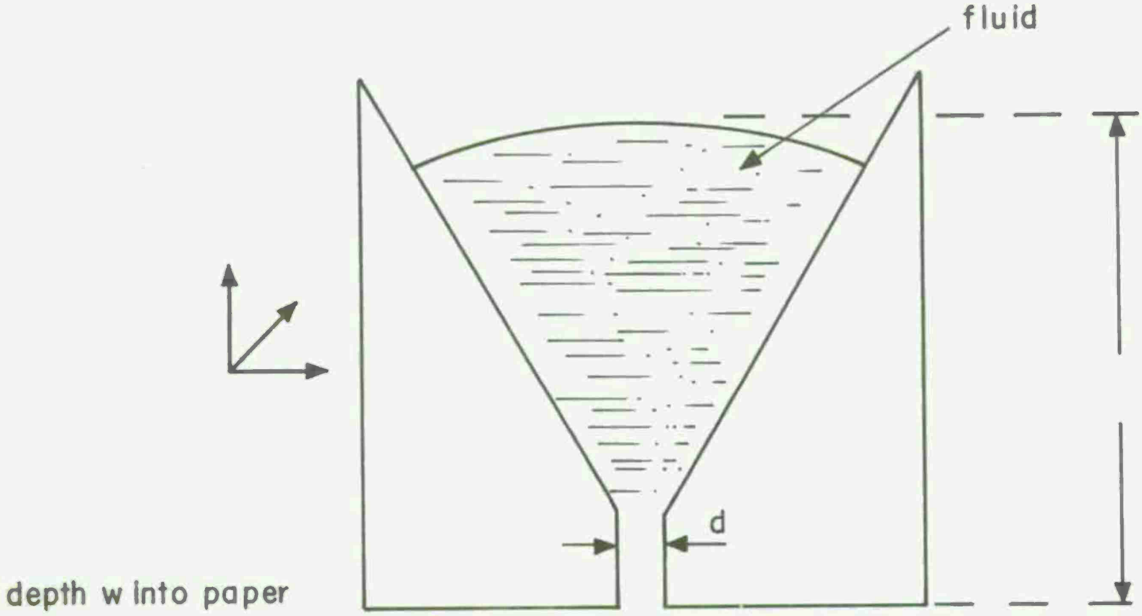


Figure 8. Schematic of Universal Machine with Coordinates

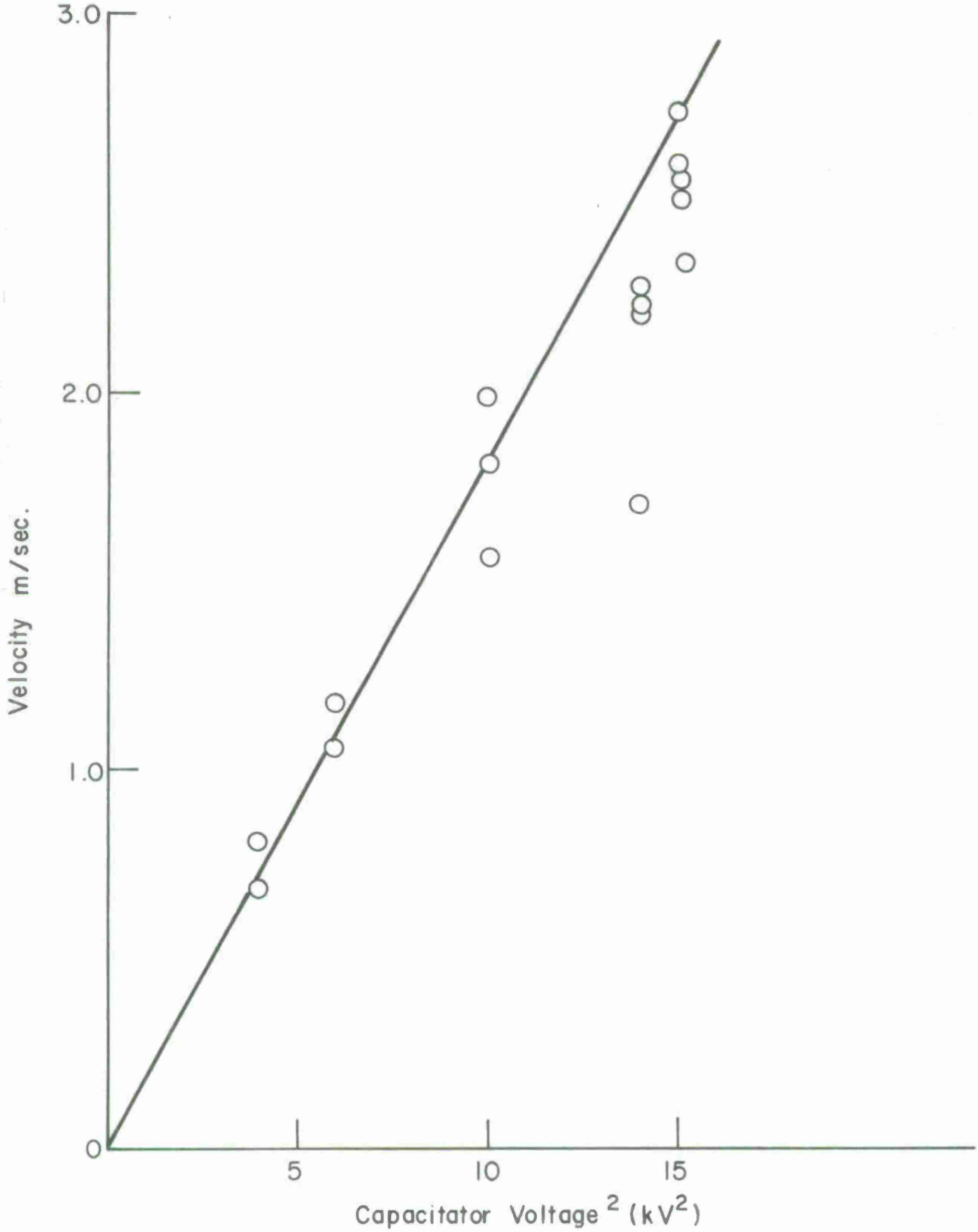


Figure 9. Results of Pendulum Experiment

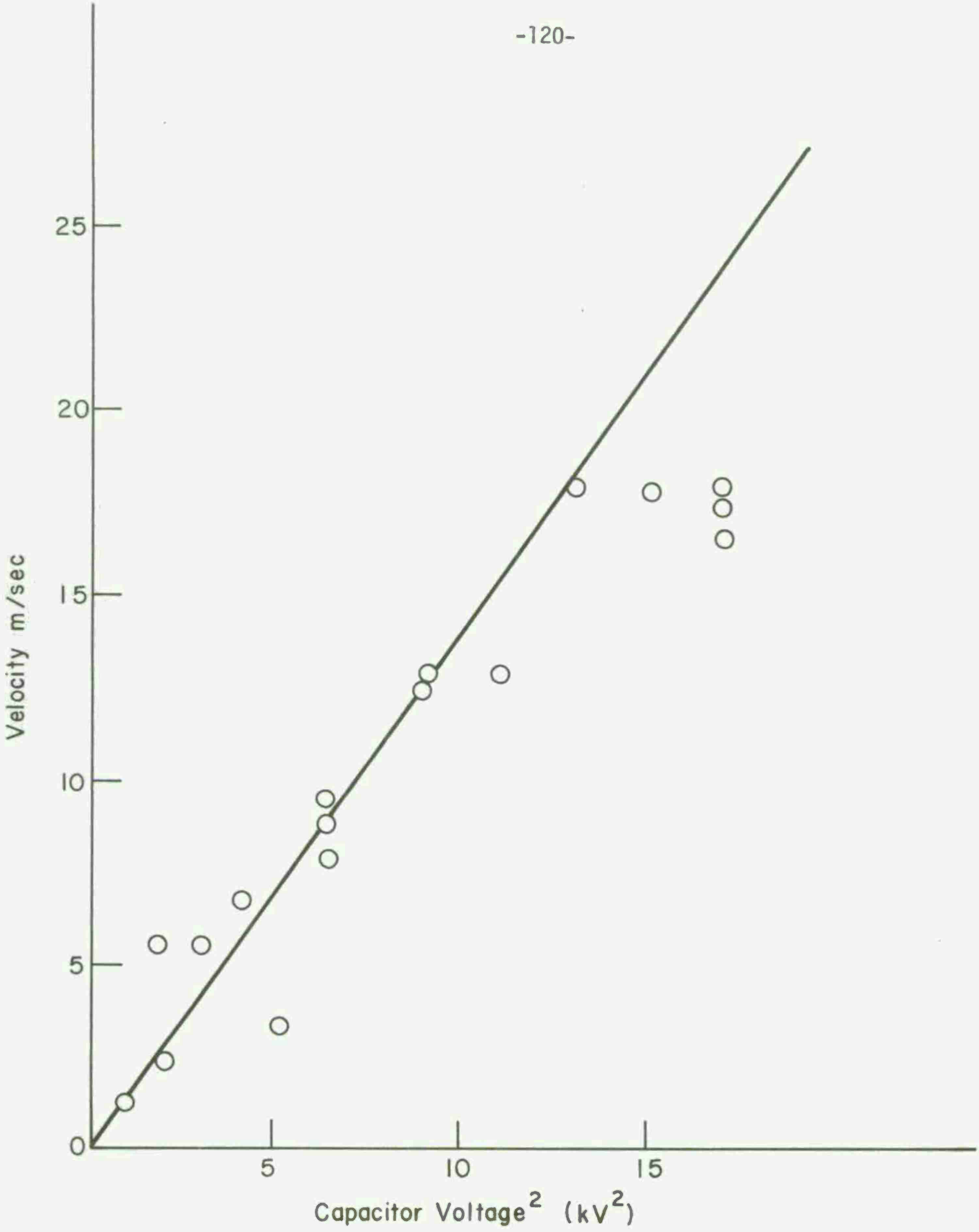


Figure 10. Results of Driver Experiment

TECHNICAL REPORT DISTRIBUTION

No. of Copies	To
1	Office of the Director, Defense Research and Engineering, The Pentagon, Washington, D. C. 20301
12	Commander, Defense Documentation Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, Virginia 22314
1	Metals and Ceramics Information Center, Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio 43201
	Chief of Research and Development, Department of the Army, Washington, D. C. 20310
2	ATTN: Physical and Engineering Sciences Division
	Commander, Army Research Office (Durham), Box CM, Duke Station, Durham, North Carolina 27706
1	ATTN: Information Processing Office
	Commander, U. S. Army Materiel Command, 5001 Eisenhower Ave., Alexandria, Virginia 22304
1	ATTN: AMCRD-TC
	Commander, Deseret Test Center, Fort Douglas, Utah 84113
1	ATTN: Technical Information Office
	Commander, U. S. Army Electronics Command, Fort Monmouth, New Jersey 07703
1	ATTN: AMSEL-GG-DD
1	AMSEL-GG-DM
	Commander, U. S. Army Missile Command, Redstone Arsenal, Alabama 35809
1	ATTN: Technical Library
1	AMSMI-RSM, Mr. E. J. Wheelahan
	Commander, U. S. Army Armament Command, Rock Island, Illinois 61201
1	ATTN: AMSAR-SC, Dr. C. M. Hudson
1	AMSAR-PPW-PB, Mr. Francis X. Walter
2	Technical Library
	Commander, U. S. Army Satellite Communications Agency, Fort Monmouth, New Jersey 07703
1	ATTN: Technical Document Center
	Commander, U. S. Army Tank-Automotive Command, Warren, Michigan 48090
2	ATTN: AMSTA-BSL, Research Library Branch
	Commander, White Sands Missile Range, New Mexico 88002
1	ATTN: STEWS-WS-VT

No. of Copies	To
	Commander, Aberdeen Proving Ground, Maryland 21005
1	ATTN: STEAP-TL, Bldg. 305
	Commander, Frankford Arsenal, Philadelphia, Pennsylvania 19137
1	ATTN: Library, H1300, Bl. 51-2
	Commander, Picatinny Arsenal, Dover, New Jersey 07801
1	ATTN: SMUPA-RT-S
	Commander, Redstone Scientific Information Center, U. S. Army Missile Command, Redstone Arsenal, Alabama 35809
4	ATTN: AMSMI-RBLD, Document Section
	Commander, Watervliet Arsenal, Watervliet, New York 12189
1	ATTN: SWEWV-RDT, Technical Information Services Office
	Commander, U. S. Army Foreign Science and Technology Center, 220 7th Street, N. E., Charlottesville, Virginia 22901
1	ATTN: AMXST-SD3
	Director, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia 23604
1	ATTN: Mr. J. Robinson, SAVDL-EU-SS
	Librarian, U. S. Army Aviation School Library, Fort Rucker, Alabama 36360
1	ATTN: Building 5907
	Commander, USACDC Ordnance Agency, Aberdeen Proving Ground, Maryland 21005
2	ATTN: Library, Building 305
	Naval Research Laboratory, Washington, D. C. 20375
1	ATTN: Dr. J. M. Krafft - Code 8430
	Chief of Naval Research, Arlington, Virginia 22217
1	ATTN: Code 471
	Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433
2	ATTN: AFML (LAE), E. Morrissey
1	AFML (LC)
1	AFML (LMD), D. M. Forney
	National Aeronautics and Space Administration, Washington, D. C. 20546
1	ATTN: Mr. B. G. Achhammer
1	Mr. G. C. Deutsch - Code RR-1
	National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama 35812
1	ATTN: R-P&VE-M, R. J. Schwinghamer
1	S&E-ME-MM, Mr. W. A. Wilson, Building 4720

No. of Copies	To
	Wyman-Gordon Company, Worcester, Massachusetts 01601
1	ATTN: Technical Library
	Defense Research Projects Agency, 1400 Wilson Boulevard, Arlington, Virginia 22209
5	ATTN: Dr. E. C. VanReuth
	National Science Foundation, 1800 G Street, Washington, D. C. 20550
1	ATTN: Dr Robert Reynik
1	Dr. Maurice Sinnott, University of Michigan, Assoc. Dir. of Engineering, Ann Arbor, Michigan 48104
	General Electric Company, Corporate Research and Development, Schenectady, New York 12301
5	ATTN: Mr. F. X. Gigliotti, Jr.
	Hitchiner Manufacturing Co., Inc., Elm Street, Milford, New Hampshire 03055
5	ATTN: Mr. G. D. Chandley
	Abex Corporation, Research Center, Mahwah, New Jersey 07430
5	ATTN: H. R. Larson
	Massachusetts Institute of Technology, Dept. of Metallurgy and Materials Science, Cambridge, Massachusetts 02139
5	ATTN: Dr. Merton C. Fleming
1	Fred E. Ziter, Adirondack Steel Casting Co., Shaker Road, Watervliet, New York 12189
1	Dr. Raymond J. Bratton, Westinghouse Electric Corporation Research Laboratory, Pittsburgh, Pennsylvania 15235
1	Lt. Col. Edward E. Chick, Chief, Materials Branch, U. S. Army R&D Group (Europe), Box 15, FPO New York 09510
1	TRW Equipment, TRW Inc., 23555 Euclid Avenue, Cleveland, Ohio 44117
1	ATTN: Elizabeth Barrett, T/M 3417
1	W. M. Spurgeon, Director, Mfg., Qual. Control & Home Systems, Program Management Center, Bendix Research Laboratories, Bendix Center Southfield, Michigan 48075
1	S. T. Wlodek, Director of Stellite R&D, Stellite Division, Cabot Corporation, 1020 West Park Avenue, Kokomo, Indiana 46901
	Deposite & Composites Inc., 1821 Michael Faraday Drive, Reston, Virginia 22090
1	ATTN: Richard E. Engdahl, President

No. of Copies	To
1	Mr. William A. Butler, Contract Administrator, Microwave Associates, Inc., Burlington, Massachusetts 01803
1	Mr. John A. Ulrich, Sr. Vice-President, Chamberlain Manufacturing Corp., Waterloo, Iowa 50705
1	A. V. Illyn, Technical Director, Babcock & Wilcox, Old Savannah Road, Augusta, Georgia 30903
1	Mr. W. J. Welsch (Code 224), Naval Materials Industry Resources Office, N.A.E.C., Building #537, Philadelphia, Pennsylvania 19112
1	Mr. R. E. Cross, Federal Die Casting Co., 2222 Elston Avenue, Chicago, Illinois 60614
1	Captain Ebenezer F. Porter, 2618 S. Lynn Street, Arlington, Virginia 22202
1	Mr. Charles E. Bates, Head, Metallurgy Section, Southern Research Institute, 2000 Ninth Avenue, South, Birmingham, Alabama 35205
	Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172
2	ATTN: AMXMR-PL
1	AMXMR-PR
1	AMXMR-CT
1	AMXMR-X
1	AMXMR-XC
1	AMXMR-ER
1	AMXMR-AP
1	Mr. R. F. Kirby, Chief, Materials Engineering Dept., Dept. 93-39M, Airesearch Manufacturing Company of Arizona, 402 South 36th Street, Phoenix, Arizona 85034

No. of Copies	To
1	Mr. Richard E. Engdahl, President, Deposits & Composites Incorporated, 1821 Michael Faraday Drive, Reston, Virginia 22090
1	IIT Research Institute, 10 West 35th Street, Chicago, Illinois 60616 ATTN: Dr. Kishor Kulkarni, Manager, Metalworking Research
1	TRW Equipment, 23555 Euclid Avenue, Cleveland, Ohio, 44117 ATTN: Ms. Elizabeth Barrett, T/M 3417
1	Air Force Materials Laboratory, Wright-Patterson AFB, Ohio 45433 ATTN: AFML (LTM), Mr. H. Johnson
1	Mr. Fred E. Ziter, Adirondack Steel Casting Company, P. O. Box 109, Latham, New York 12210
1	Westinghouse Electric Corporation, Pittsburgh, Pennsylvania 15235 ATTN: Dr. Raymond J. Bratton, Research Laboratory
1	Mr. Joseph C. Benedyk, Technical Products Division, Brunswick Corporation, Brunswick Plaza, Skokie, Illinois 60076
1	Mr. A. H. Hauser, Manager, Materials Engineering & Research Laboratory, Pratt & Whitney Aircraft Division, United Aircraft Corporation, East Hartford, Connecticut 06108
1	Dr. Wally Evans, Ford Motor Company, Casting Division, Room 1350, 3001 Miller Road, Dearborn, Michigan 48121

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AMMRC CTR 75-22	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MACHINE CASTING OF FERROUS ALLOYS		5. TYPE OF REPORT & PERIOD COVERED Interim Report 1 July 1974 - 30 June 1975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) M.C. Flemings, R. Mehrabian, J.R. Melcher, R.G. Riek, K.P. Young, N. Matsumoto D.G.Backman, F.S. Blackall, B.E. Bond, E.J. McHale F.S. Schottman		8. CONTRACT OR GRANT NUMBER(s) DAAG-46-73-C-0110
9. PERFORMING ORGANIZATION NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 2267 AMCMS Code: 4D10 Agency Accession:
11. CONTROLLING OFFICE NAME AND ADDRESS Army Materials and Mechanics Research Center Watertown, Massachusetts 02172		12. REPORT DATE October 1975
		13. NUMBER OF PAGES 120
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Die Casting
Solidification

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the third interim report describing research conducted at Massachusetts Institute of Technology as part of a joint university-industry research program on casting of ferrous alloys. It covers the period of the eighteenth to the thirthieth month of a four-year program. During this period the "Continuous Rheocaster" has been greatly improved and a machine casting system using semi-solid alloys "Thixocasting" has been developed and operated on pilot basis using a copper base alloy.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Work has also continued on low temperature "model" systems, and on other supporting studies.

The high temperature "Continuous Rheocaster" described earlier has undergone extensive modification and development. It has been used to continuously produce a number of ferrous alloy slurries and a cobalt base superalloy slurry. The apparatus has now been optimized for continuous production of larger quantities of "Rheocast" ingots, and several hundred pounds have been produced of the "model" bronze alloy employed previously (905 alloy 88wt%Cu, 10wt%Cu, 10wt%Sn, 2wt%Zn). These ingots have been cut to size, reheated to the semi-solid range, coupled to a commercial 125 ton cold chamber die cast machine. To date, more than 150 castings of a simulated D.O.D. part have been made in the bronze alloy. Results of this work confirm that castings with good surface quality are obtained with internal soundness substantially improved over that of die castings made from superheated metal.

Internal die temperature measurements were made during the casting of both liquid and semi-solid bronze alloy 905. Computer calculations indicate that use of semi-solid charge, as opposed to superheated liquid charge, significantly reduces die surface temperature, (by a factor of 4), rate of surface heating, (by a factor of 7), and maximum surface temperature gradient, (by a factor of 8).

The low temperature "Continuous Rheocaster" has been used with the model Sn-Pb alloys employed previously to examine the effects on the slurry structure of cooling rate, shear rate, composition and volume fraction solid. Primary particle size decreased markedly with increasing cooling rate, in the range 0-800°C min.$^{-1}$ and to a lesser extent with increasing shear rate in the range 0-1000 sec.$^{-1}$. Particle size increased with fraction solid, particle sizes were in the range of 60-250μm. The successful production of pure Sn, Sn-Pb eutectic and near eutectic slurries has confirmed the feasibility of Rheocasting alloys of narrow freezing range.

The feasibility of a modified "Thixocasting" process termed "Clap Casting" has been demonstrated using as a model an aluminum-copper alloy. This process eliminates both crucible and alloy injection equipment while automating metal transfer. It is, therefore, particularly attractive for high temperature alloys.

Two different types of electromagnetic injectors have also been studied and comparisons between them made on the basis of experiment and theory. The first is an "induction" machine described earlier, the second is a "universal" machine. Theory and experiment agree well in both machines. A simply and inexpensively constructed apparatus can propel metal at velocities of 20 m/sec. corresponding to casting pressures of 400 psi.

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
MACHINE CASTING OF FERROUS ALLOYS
M.C. Flemings, R. Mehrabian, J.R. Melcher
R.G. Riek, K.P. Young, N. Matsumoto
D.G. Backman, F.S. Blackall, B.E. Bond,
E.J. McHale, F.S. Schottman

AD__________________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Technical Report AMMRC CTR 75-22, October 1975
120 pp - illustrations, D/A Project ARPA
Order No. 2267, AMCMS Code 4D10

Die Casting
Solidification

This is the third interim report describing research conducted at Massachusetts Institute of Technology as part of a joint university-industry research program on casting of ferrous alloys. It covers the period of the eighteenth to the thirthieth month of a four-year program. During this period the "Continuous Rheocaster" has been greatly improved and a machine casting system using semi-solid alloys "Thixocasting" has been developed and operated on pilot basis using a copper base alloy. Work has also continued on low temperature "model" systems, and on other supporting studies. The high temperature "Continuous Rheocaster" described earlier has undergone extensive modification and development. It has been used to continuously produce a number of ferrous alloy slurries and a cobalt base superalloy slurry. The apparatus has now been optimized for continuous production of larger quantities of "Rheocast" ingots, and several hundred pounds have been produced of the "model" bronze alloy employed previously (905 alloy 99wt%Cu, 10wt%Cu, 10wt%Sn, 2wt%Zn). These ingots have been cut to size, reheated to the semi-solid range and cast using a newly developed "Thixocasting" system. This comprises an induction furnace to rapidly reheat the ingot sections to the semi-solid range, coupled to a commercial 125 ton cold chamber die cast machine. To date, more than 150 castings of a simulated D.O.D. part have been made in the bronze alloy. Results of this work confirm that castings with good surface quality are obtained with internal soundness substantially improved over that of die castings made from superheated metal. Internal die temperature measurements were made during the casting of both liquid and semi-solid bronze alloy 905. Computer calculations indicate that use of semi-solid charge as opposed to superheated liquid charge, significantly reduces die surface temperature (by a factor of 4), rate of surface heating, (by a factor of 7), and maximum surface temperature gradient, (by a factor of 8). The low temperature "Continuous Rheocaster" has been used with the model Sn-Pb alloys employed previously to examine the effects on the slurry structure of cooling rate, shear rate, composition and volume fraction solid. Primary particle size decreased markedly with increasing cooling rate, in the range 0-800°C $min.^{-1}$ and to a lesser extent with increasing shear rate in the range 0-1000 $sec.^{-1}$. Particle size increased with fraction solid, particle sizes were in the range of 60-250μm. The successful production of pure Sn, Sn-Pb eutectic and near eutectic slurries has confirmed the feasibility of Rheocasting alloys of narrow freezing range. The feasibility of a modified "Thixocasting" process termed "Clap Casting" has been demonstrated using as a model an aluminum-copper alloy. This process eliminates both crucible and alloy injection equipment while automating metal transfer. It is, therefore, particularly attractive for high temperature alloys. Two different types of electromagnetic injectors have also been studied and comparisons between them made on the basis of experiment and theory. The first is an "induction" machine described earlier, the second is a "universal" machine. Theory and experiment agree well in both machines. A simply an inexpensively constructed apparatus can propel metal at velocities of 20 m/sec. corresponding to casting pressures of 400 psi.

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
MACHINE CASTING OF FERROUS ALLOYS
M.C. Flemings, R. Mehrabian, J.R. Melcher
R.G. Riek, K.P. Young, N. Matsumoto
D.G. Backman, F.S. Blackall, B.E. Bond,
E.J. McHale, F.S. Schottman

AD__________________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Technical Report AMMRC CTR 75-22, October 1975
120 pp - illustrations, D/A Project ARPA
Order No. 2267, AMCMS Code 4D10

Die Casting
Solidification

This is the third interim report describing research conducted at Massachusetts Institute of Technology as part of a joint university-industry research program on casting of ferrous alloys. It covers the period of the eighteenth to the thirthieth month of a four-year program. During this period the "Continuous Rheocaster" has been greatly improved and a machine casting system using semi-solid alloys "Thixocasting" has been developed and operated on pilot basis using a copper base alloy. Work has also continued on low temperature "model" systems, and on other supporting studies. The high temperature "Continuous Rheocaster" described earlier has undergone extensive modification and development. It has been used to continuously produce a number of ferrous alloy slurries and a cobalt base superalloy slurry. The apparatus has now been optimized for continuous production of larger quantities of "Rheocast" ingots, and several hundred pounds have been produced of the "model" bronze alloy employed previously (905 alloy 99wt%Cu, 10wt%Cu, 10wt%Sn, 2wt%Zn). These ingots have been cut to size, reheated to the semi-solid range and cast using a newly developed "Thixocasting" system. This comprises an induction furnace to rapidly reheat the ingot sections to the semi-solid range, coupled to a commercial 125 ton cold chamber die cast machine. To date, more than 150 castings of a simulated D.O.D. part have been made in the bronze alloy. Results of this work confirm that castings with good surface quality are obtained with internal soundness substantially improved over that of die castings made from superheated metal. Internal die temperature measurements were made during the casting of both liquid and semi-solid bronze alloy 905. Computer calculations indicate that use of semi-solid charge as opposed to superheated liquid charge, significantly reduces die surface temperature (by a factor of 4), rate of surface heating, (by a factor of 7), and maximum surface temperature gradient, (by a factor of 8). The low temperature "Continuous Rheocaster" has been used with the model Sn-Pb alloys employed previously to examine the effects on the slurry structure of cooling rate, shear rate, composition and volume fraction solid. Primary particle size decreased markedly with increasing cooling rate, in the range 0-800°C $min.^{-1}$ and to a lesser extent with increasing shear rate in the range 0-1000 $sec.^{-1}$. Particle size increased with fraction solid, particle sizes were in the range of 60-250μm. The successful production of pure Sn, Sn-Pb eutectic and near eutectic slurries has confirmed the feasibility of Rheocasting alloys of narrow freezing range. The feasibility of a modified "Thixocasting" process termed "Clap Casting" has been demonstrated using as a model an aluminum-copper alloy. This process eliminates both crucible and alloy injection equipment while automating metal transfer. It is, therefore, particularly attractive for high temperature alloys. Two different types of electromagnetic injectors have also been studied and comparisons between them made on the basis of experiment and theory. The first is an "induction" machine described earlier, the second is a "universal" machine. Theory and experiment agree well in both machines. A simply an inexpensively constructed apparatus can propel metal at velocities of 20 m/sec. corresponding to casting pressures of 400 psi.

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
MACHINE CASTING OF FERROUS ALLOYS
M.C. Flemings, R. Mehrabian, J.R. Melcher
R.G. Riek, K.P. Young, N. Matsumoto
D.G. Backman, F.S. Blackall, B.E. Bond,
E.J. McHale, F.S. Schottman

AD__________________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Technical Report AMMRC CTR 75-22, October 1975
120 pp - illustrations, D/A Project ARPA
Order No. 2267, AMCMS Code 4D10

Die Casting
Solidification

This is the third interim report describing research conducted at Massachusetts Institute of Technology as part of a joint university-industry research program on casting of ferrous alloys. It covers the period of the eighteenth to the thirthieth month of a four-year program. During this period the "Continuous Rheocaster" has been greatly improved and a machine casting system using semi-solid alloys "Thixocasting" has been developed and operated on pilot basis using a copper base alloy. Work has also continued on low temperature "model" systems, and on other supporting studies. The high temperature "Continuous Rheocaster" described earlier has undergone extensive modification and development. It has been used to continuously produce a number of ferrous alloy slurries and a cobalt base superalloy slurry. The apparatus has now been optimized for continuous production of larger quantities of "Rheocast" ingots, and several hundred pounds have been produced of the "model" bronze alloy employed previously (905 alloy 99wt%Cu, 10wt%Cu, 10wt%Sn, 2wt%Zn). These ingots have been cut to size, reheated to the semi-solid range and cast using a newly developed "Thixocasting" system. This comprises an induction furnace to rapidly reheat the ingot sections to the semi-solid range, coupled to a commercial 125 ton cold chamber die cast machine. To date, more than 150 castings of a simulated D.O.D. part have been made in the bronze alloy. Results of this work confirm that castings with good surface quality are obtained with internal soundness substantially improved over that of die castings made from superheated metal. Internal die temperature measurements were made during the casting of both liquid and semi-solid bronze alloy 905. Computer calculations indicate that use of semi-solid charge as opposed to superheated liquid charge, significantly reduces die surface temperature (by a factor of 4), rate of surface heating, (by a factor of 7), and maximum surface temperature gradient, (by a factor of 8). The low temperature "Continuous Rheocaster" has been used with the model Sn-Pb alloys employed previously to examine the effects on the slurry structure of cooling rate, shear rate, composition and volume fraction solid. Primary particle size decreased markedly with increasing cooling rate, in the range 0-800°C $min.^{-1}$ and to a lesser extent with increasing shear rate in the range 0-1000 $sec.^{-1}$. Particle size increased with fraction solid, particle sizes were in the range of 60-250μm. The successful production of pure Sn, Sn-Pb eutectic and near eutectic slurries has confirmed the feasibility of Rheocasting alloys of narrow freezing range. The feasibility of a modified "Thixocasting" process termed "Clap Casting" has been demonstrated using as a model an aluminum-copper alloy. This process eliminates both crucible and alloy injection equipment while automating metal transfer. It is, therefore, particularly attractive for high temperature alloys. Two different types of electromagnetic injectors have also been studied and comparisons between them made on the basis of experiment and theory. The first is an "induction" machine described earlier, the second is a "universal" machine. Theory and experiment agree well in both machines. A simply an inexpensively constructed apparatus can propel metal at velocities of 20 m/sec. corresponding to casting pressures of 400 psi.

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
MACHINE CASTING OF FERROUS ALLOYS
M.C. Flemings, R. Mehrabian, J.R. Melcher
R.G. Riek, K.P. Young, N. Matsumoto
D.G. Backman, F.S. Blackall, B.E. Bond,
E.J. McHale, F.S. Schottman

AD__________________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Key Words

Technical Report AMMRC CTR 75-22, October 1975
120 pp - illustrations, D/A Project ARPA
Order No. 2267, AMCMS Code 4D10

Die Casting
Solidification

This is the third interim report describing research conducted at Massachusetts Institute of Technology as part of a joint university-industry research program on casting of ferrous alloys. It covers the period of the eighteenth to the thirthieth month of a four-year program. During this period the "Continuous Rheocaster" has been greatly improved and a machine casting system using semi-solid alloys "Thixocasting" has been developed and operated on pilot basis using a copper base alloy. Work has also continued on low temperature "model" systems, and on other supporting studies. The high temperature "Continuous Rheocaster" described earlier has undergone extensive modification and development. It has been used to continuously produce a number of ferrous alloy slurries and a cobalt base superalloy slurry. The apparatus has now been optimized for continuous production of larger quantities of "Rheocast" ingots, and several hundred pounds have been produced of the "model" bronze alloy employed previously (905 alloy 99wt%Cu, 10wt%Cu, 10wt%Sn, 2wt%Zn). These ingots have been cut to size, reheated to the semi-solid range and cast using a newly developed "Thixocasting" system. This comprises an induction furnace to rapidly reheat the ingot sections to the semi-solid range, coupled to a commercial 125 ton cold chamber die cast machine. To date, more than 150 castings of a simulated D.O.D. part have been made in the bronze alloy. Results of this work confirm that castings with good surface quality are obtained with internal soundness substantially improved over that of die castings made from superheated metal. Internal die temperature measurements were made during the casting of both liquid and semi-solid bronze alloy 905. Computer calculations indicate that use of semi-solid charge as opposed to superheated liquid charge, significantly reduces die surface temperature (by a factor of 4), rate of surface heating, (by a factor of 7), and maximum surface temperature gradient, (by a factor of 8). The low temperature "Continuous Rheocaster" has been used with the model Sn-Pb alloys employed previously to examine the effects on the slurry structure of cooling rate, shear rate, composition and volume fraction solid. Primary particle size decreased markedly with increasing cooling rate, in the range 0-800°C $min.^{-1}$ and to a lesser extent with increasing shear rate in the range 0-1000 $sec.^{-1}$. Particle size increased with fraction solid, particle sizes were in the range of 60-250μm. The successful production of pure Sn, Sn-Pb eutectic and near eutectic slurries has confirmed the feasibility of Rheocasting alloys of narrow freezing range. The feasibility of a modified "Thixocasting" process termed "Clap Casting" has been demonstrated using as a model an aluminum-copper alloy. This process eliminates both crucible and alloy injection equipment while automating metal transfer. It is, therefore, particularly attractive for high temperature alloys. Two different types of electromagnetic injectors have also been studied and comparisons between them made on the basis of experiment and theory. The first is an "induction" machine described earlier, the second is a "universal" machine. Theory and experiment agree well in both machines. A simply an inexpensively constructed apparatus can propel metal at velocities of 20 m/sec. corresponding to casting pressures of 400 psi.